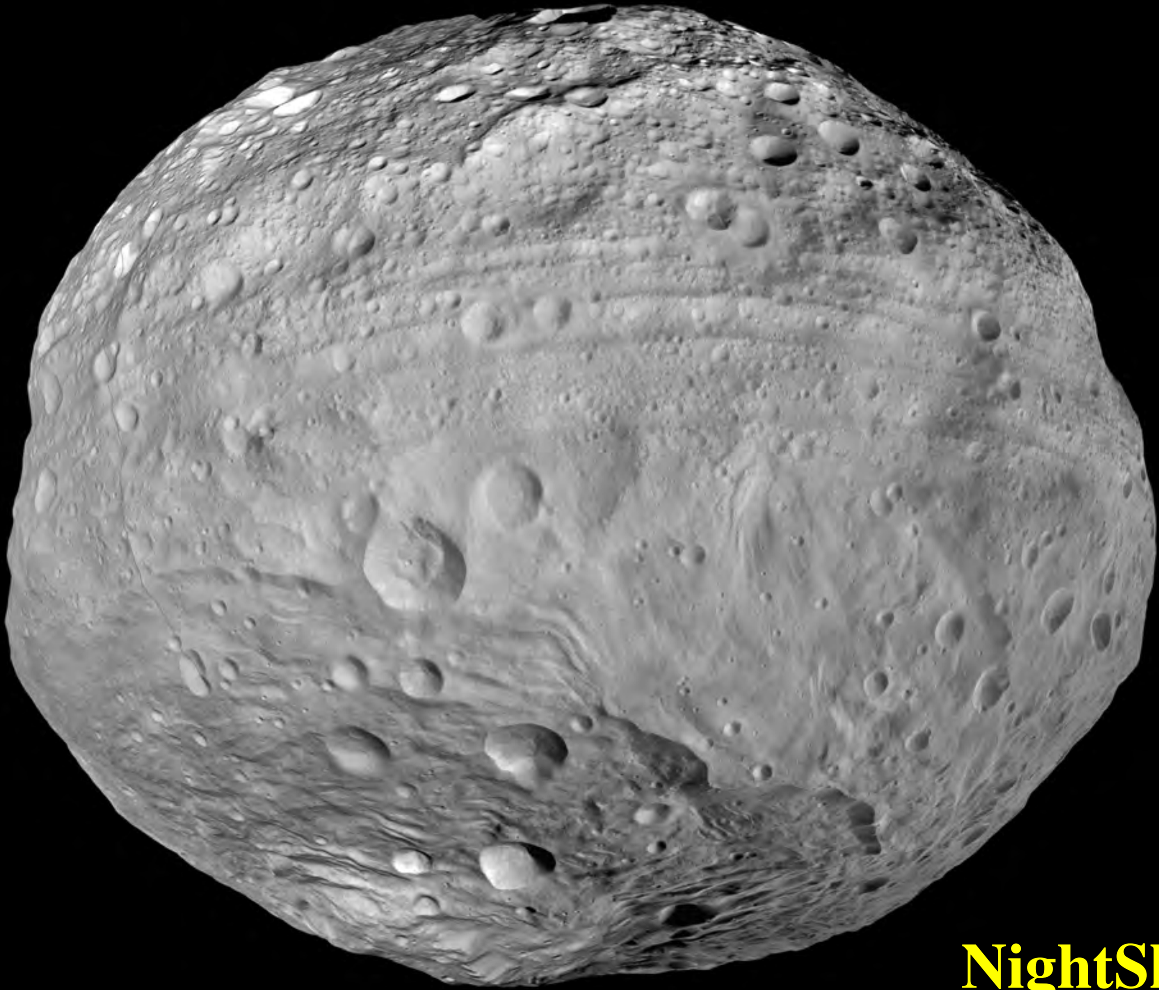
Asteroids, Ion Propulsion, and NASA's *Dawn* Mission to Vesta & Ceres



Dr. David A. Williams
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NightSky Network
Online Talk
August 27, 2014

HOW DO WE EXPLORE THE SOLAR SYSTEM?

Phased Approach:

- Do What's Technically Possible
- Do What's Affordable
- Do the Easy Missions First (Successfully), Then More Complex

SSE: Missions of Increasing Difficulty & Complexity

- Planetary Fly-by (Initial reconnaissance)
- Planetary Orbiter (Global assessment of surface)
- Planetary Lander: Hard Landers, Then Soft Landers
- Planetary Rover: Mobility on Land or in Atmosphere
- Planetary Sample Return: Study Rock/Soil/Air Samples in Lab
- Outer Satellite Orbiter/Lander
- Manned Missions: Orbiting, Landing

SOLAR SYSTEM EXPLORATION 2014

Planet	Telescopic Observation	Flyby	Orbiter	Lander	Rover	Sample Return	Manned Mission
Mercury	1610	Mar10	MES				
Venus	1610	Mar2	Ven9	Ven7	Veg1-Bal		
Earth		Gal					
Moon	1610	Lun1	Lun10	Lun2/9	Lun17	Lun16	Ap11-17
Mars	1609	Mar4	Mars2	Vik1	**MSL**	MSR	
Asteroids	1801	Gal	**DAWN**	NEAR		Hayabusa	
Comets	1618	Gio	Rosetta	Rosetta		Stardust	
Jupiter	1610	Pio10	Gal	Gal-AP	------	------	------
Io	1610	Gal					
Europa	1610	Gal	Europa Clipper				
Ganymede	1610	Gal	JUICE				
Callisto	1610	Gal					
Saturn	1610	Pio11	Cas	------	-----	----	----
Titan	1655	Cas	--------	Huy			
Enceladus	1787	Cas					
Uranus	1781	Voy2	Uranus Orbiter	-----	----	-----	-----
Neptune	1846	Voy2	-------	-----	-----	----	-----
Pluto	1930	NH-2015					
Kuiper Belt	1992	NH-2020?					

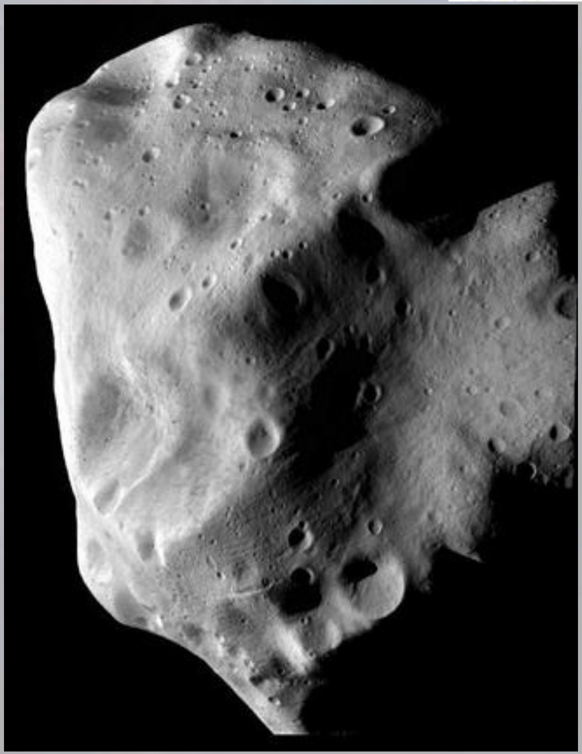
Mar=Mariner (US), MES=MESSENGER (US), BP=Bepi Columbo (ESA), Ven=Venera (USSR), Veg=Vega (USSR), Gal=Galileo (US), Lun=Luna (USSR), Ap=Apollo (US), Vik=Viking (US), MPF=Mars Pathfinder (US), Gio=Giotto (ESA), Ros=Rosetta (ESA), Pio=Pioneer (US), Cas=Cassini, Huy=Huygens (ESA), Voy=Voyager (US), NH=New Horizons (US), JUICE = Jupiter Icy Moons Explorer-Ganymede Orbiter (ESA)

Outline

- Asteroids: What and where are they?
  - ✧ Why Ceres?
  - ✧ Why Vesta?
- Ion propulsion
  - ✧ Basics of spaceflight: Why *Dawn* needs it?
  - ✧ Ion propulsion: What is it?
  - ✧ Milestones of *Dawn*' s ion propulsion
- NASA *Dawn* Mission
  - ✧ Objectives of mission
  - ✧ Instruments and Operations
  - ✧ Results so far (including VIR & GRaND data!)
- Conclusions and Q&A

Asteroids

- What are they?
  - ✧ Minor planets (protoplanets) w/diameters <500 km
  - ✧ Mostly irregularly shaped
  - ✧ Mostly composed of silicate rock, dust & volatiles
- Where are they? Mostly *Main Belt*
  - ✧ *Main Belt* found between orbits of Mars & Jupiter
  - ✧ Lagrange points of Jupiter (*Trojan* asteroids)
  - ✧ *Centaurs* occur between orbits of Jupiter & Neptune
  - ✧ Near-Earth Asteroids (NEAs) include:
    - ✧ *Amor* asteroids (1 AU $< q <$ 1.3 AU)
    - ✧ *Apollo* asteroids ($q <$ 1 AU, $a >$ 1 AU)
    - ✧ *Aten* asteroids ($a <$ 1 AU)
  - ✧ There are ~4,700 'potentially hazardous' known NEAs



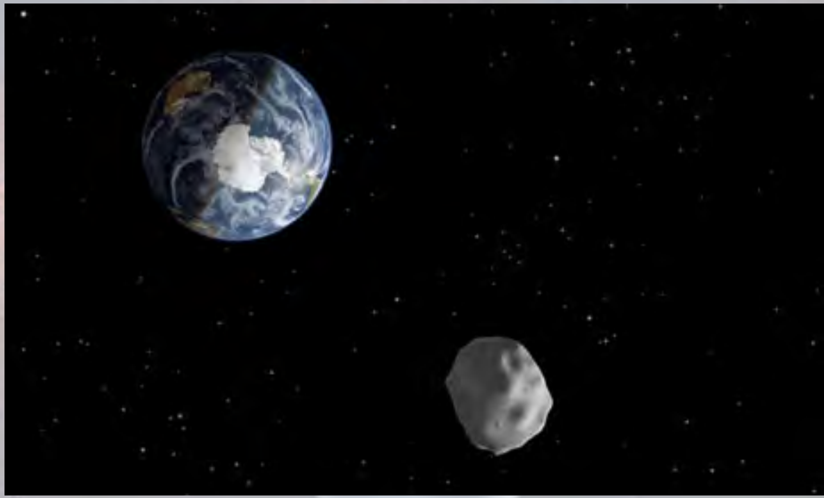
- 2012 DA14 (15 Feb 2013) was an Apollo asteroid

•Chelyabinsk (Russia, 15 Feb 2013) was a meteor that came from the Main asteroid belt

•2006 DP14 (11 Feb 2014) was a NEA

2012 DA14 Asteroid Flyby

- Occurred on Friday, Feb. 15, 2013
- Record closest approach for object this size
- Closest approach at 17,200 km, speed 7.8 m/s (17,400 mph)
  - ✧ Above ISS and low orbit satellites
  - ✧ Below geosynchronous weather satellites
  - ✧ Came in S->N: Not visible from USA
  - ✧ Radar imaged by Goldstone telescopes, CA



- 45 m long rocky asteroid
  - ✧ Same size as impactor that made Meteor Crater, AZ
    - ✧ MC: 1,200 m diameter (4,000 ft)
    - ✧ MC: 170 m deep (570 ft deep)
  - ✧ If hit, would have energy ~2.4 Megatons
  - ✧ If hit, destruction in surrounding 50 miles
  - ✧ NOT BIG ENOUGH to end civilization:
    - ✧ Chicxulub Crater, Yucatan, Mexico:
    - ✧ 180 km diameter (110 mile across)
    - ✧ Impactor: 10 km diameter (6 miles across)
    - ✧ Killed off dinosaurs 65 million years ago

Chelyabinsk (Russia) Meteor

- Occurred on Friday, Feb. 15, 2013
- Meteor came from Main asteroid belt
- Largest meteor strike in a century, since 1908 Tunguska event
- Entered atmosphere at 18 km/s (40,000 mph)
  - Estimated mass: 10,000 tons
  - Estimated size: 17 m diameter
  - Came in W->E: Not related to 2012 DA14!
- Airburst 12-15 miles above ground
  - 500 kiloton blast (500,000 tons of TNT)
  - Shock wave spread out from blast
  - Downward force of shock wave shattered windows over 200,000 sq. km:
    - ~1000 injuries (No fatalities)
    - ~4000 buildings damaged
    - Initial damage estimate US$ 33 million
  - ~53 meteorites found (Rock +10% iron)

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  - ✧ ~53 meteorites found (Ordinary Chondrite)

Asteroids

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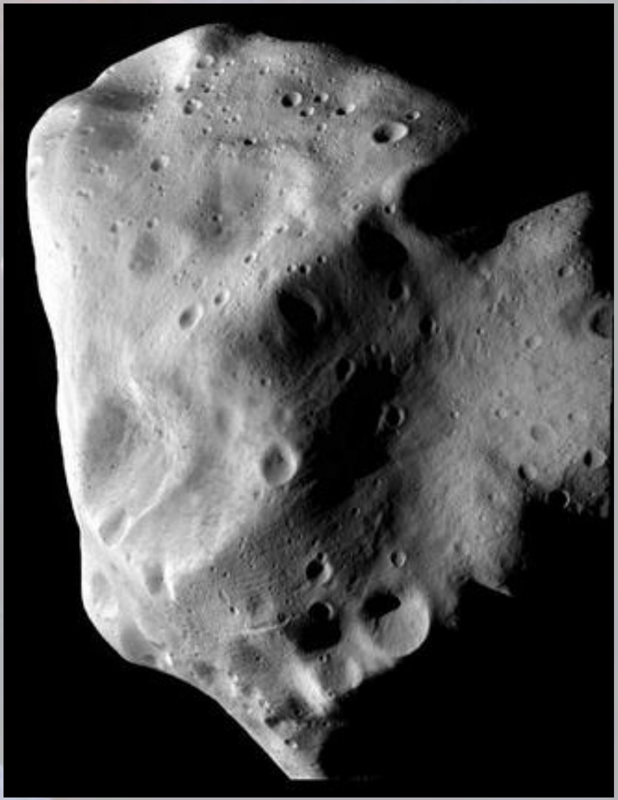
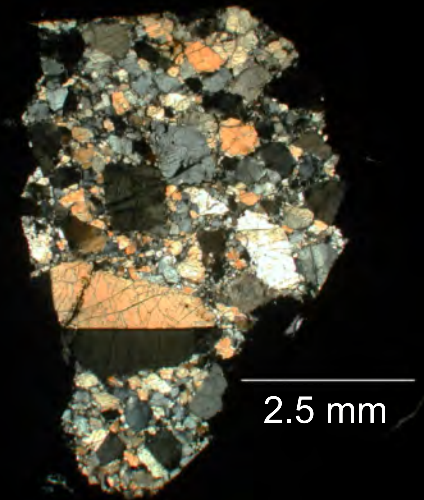


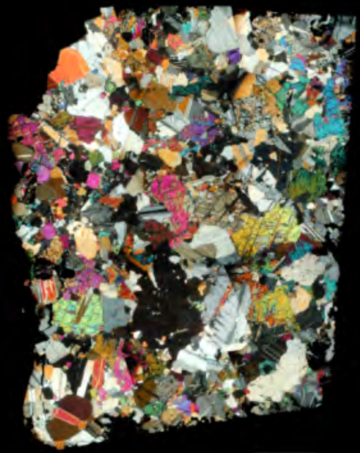
- There are 14 types of asteroids
  - Classified based on telescopic spectra
  - Largest class: C type (carbonaceous, 40%)
  - S type (stony, 30-35%)
  - D & P types (dark, primitive, 5-10%)
  - M type (metallic – iron), V type (Vesta, unique, basaltic)
- Asteroid spectra compared with meteorites in labs
- Asteroids: rocks that never coalesced into a planet

HEDs: Meteorites from Vesta?

Basaltic eucrite
basalt



Diogenite
orthopyroxenite or harzburgite

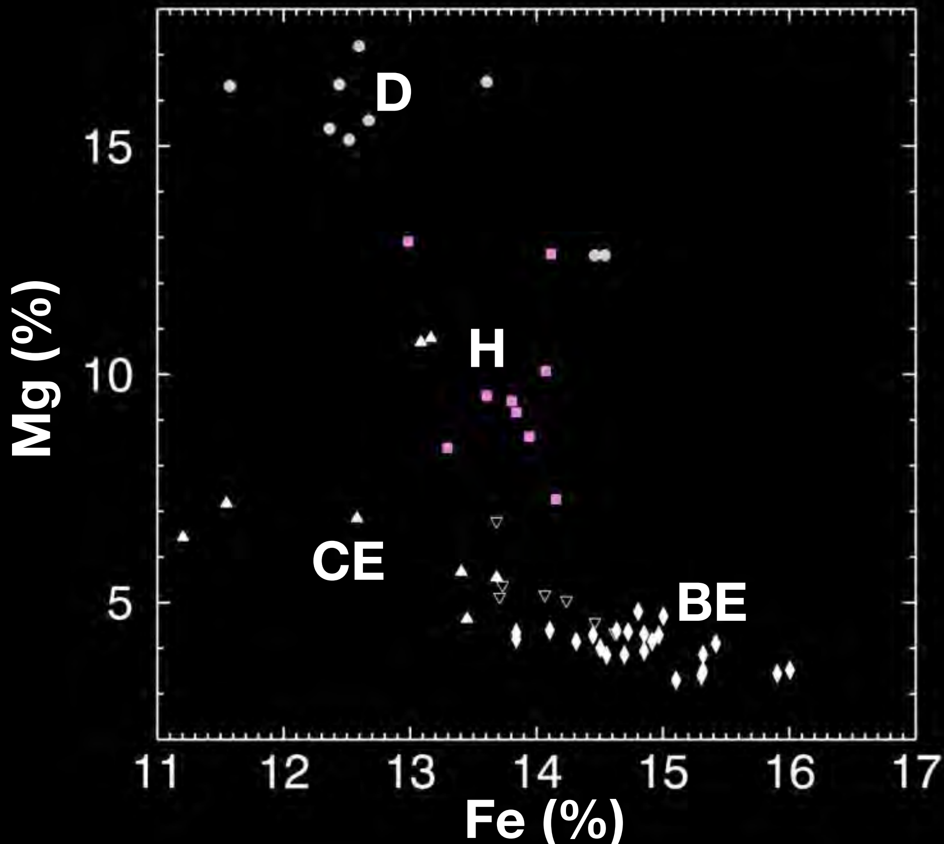


Cumulate eucrite
gabbro

Howardite
regolith breccia

Chemistry of the HEDs

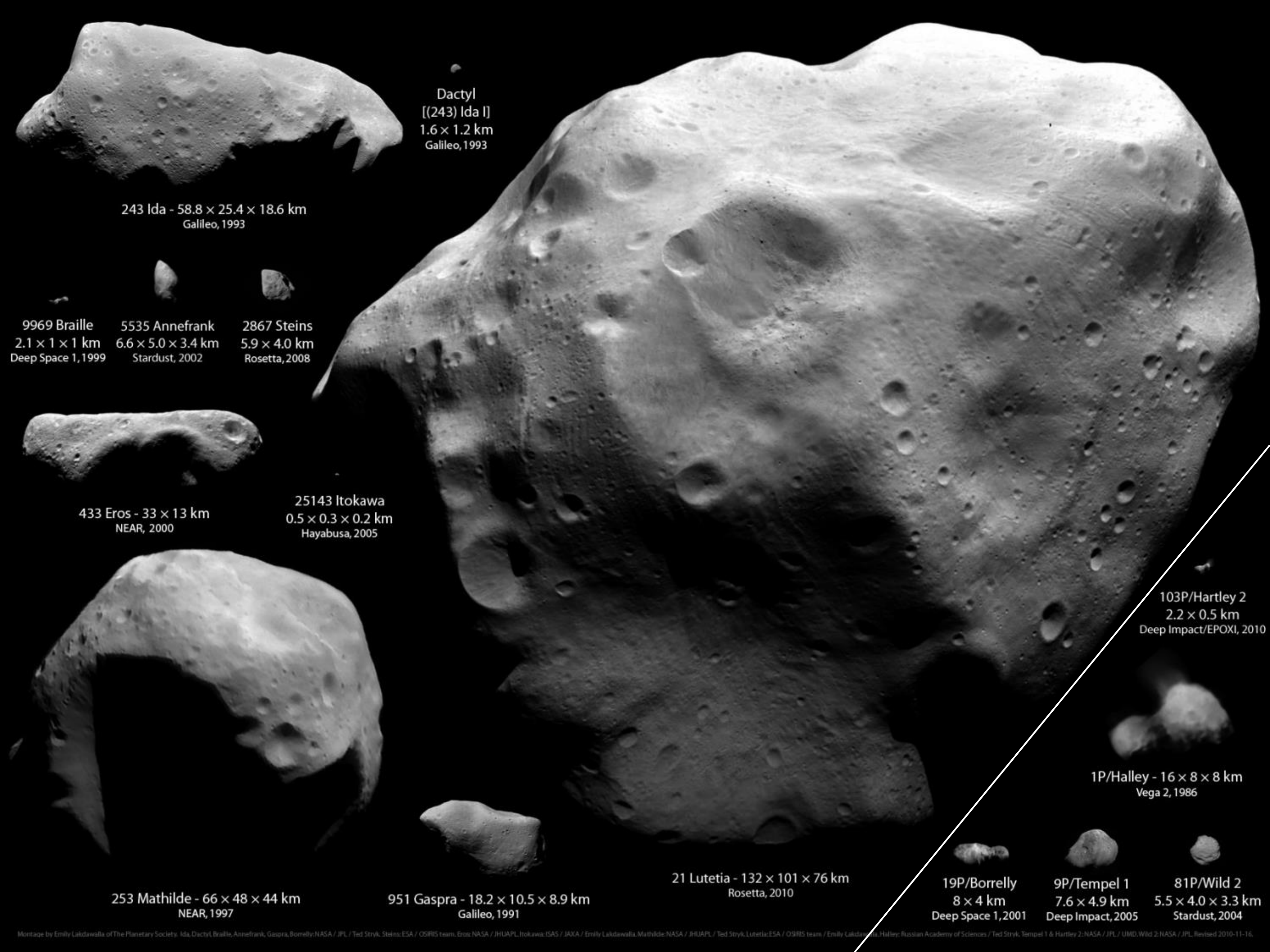
•*Dawn*' s GRaND instrument can distinguish HED whole-rock compositions

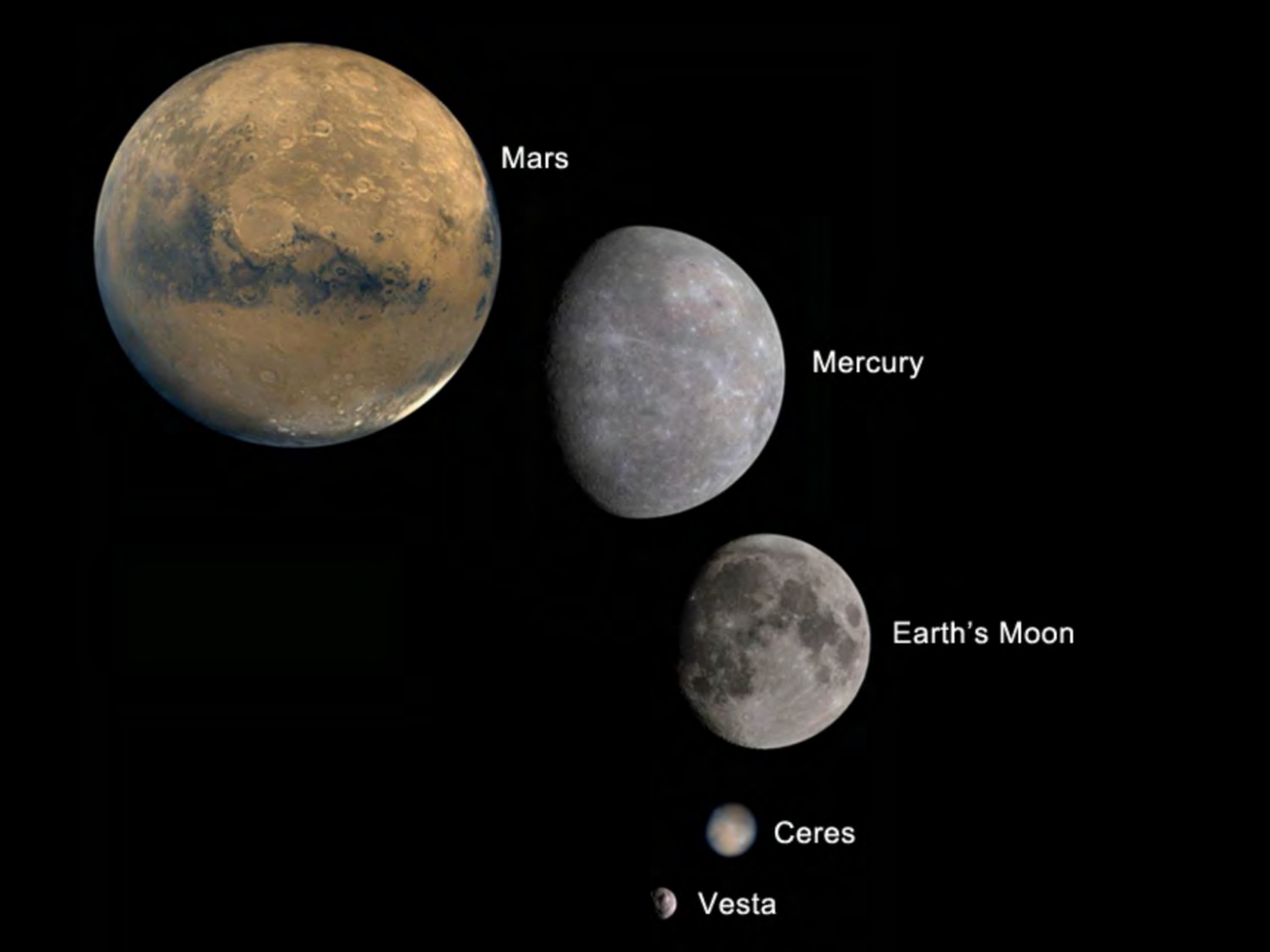


Spacecraft Exploration of Asteroids

Asteroid	*Type*	*Mission*	*Date*	*Mission Type*	*Comment*
951 Gaspra	S	*Galileo*	29Oct' 91	Flyby	First s/c encounter
243 Ida	S	*Galileo*	28Aug' 93	Flyby	First asteroidal moon
253 Mathilde	C	*NEAR*	27Jun' 97	Flyby	Flyby on way to Eros
9,969 Braille	Q	*Deep Space 1*	29Jul' 99	Flyby	Mars-crossing asteroid, DS1 tested ion engine
433 Eros	**S**	***NEAR***	**14Feb' 00**	**Orbiter**	**First asteroid orbiter**
			12Feb' 01	**Lander**	**Not designed to land**
5535 Annefrank	S	*Stardust*	02Nov' 02	Flyby	Test Comet Wild 2 flyby
25,143 Itokawa	**S**	***Hayabusa***	**12Sep' 05**	**Parking Solar Orbit**	**First sample return**
2,867 Steins	E	*Rosetta*	05Sep' 08	Flyby	Flyby on way to comet
21 Lutetia	M or C?	*Rosetta*	10Jul' 10	Flyby	Flyby on way to comet
4 Vesta	**V**	***Dawn***	**16Jul' 11**	**Orbiter**	
1 Ceres	**C**	***Dawn***	**23Mar' 15**	**Orbiter**	
101,955 Bennu	**C**	**OSIRIS-REx**	**Sep' 16**	**Orbiter-Dock-Sample Return**	

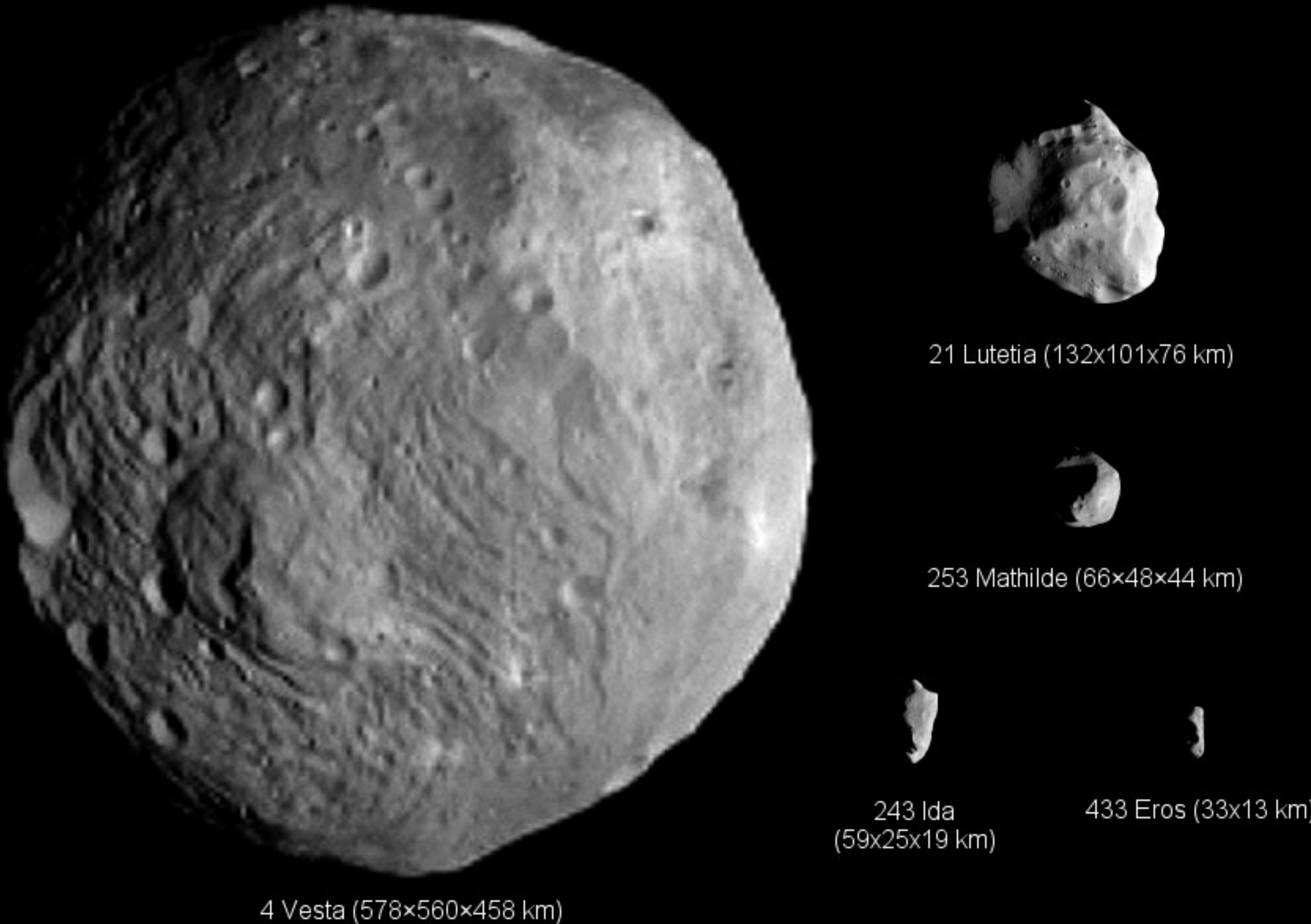
Bold = asteroid-dedicated mission

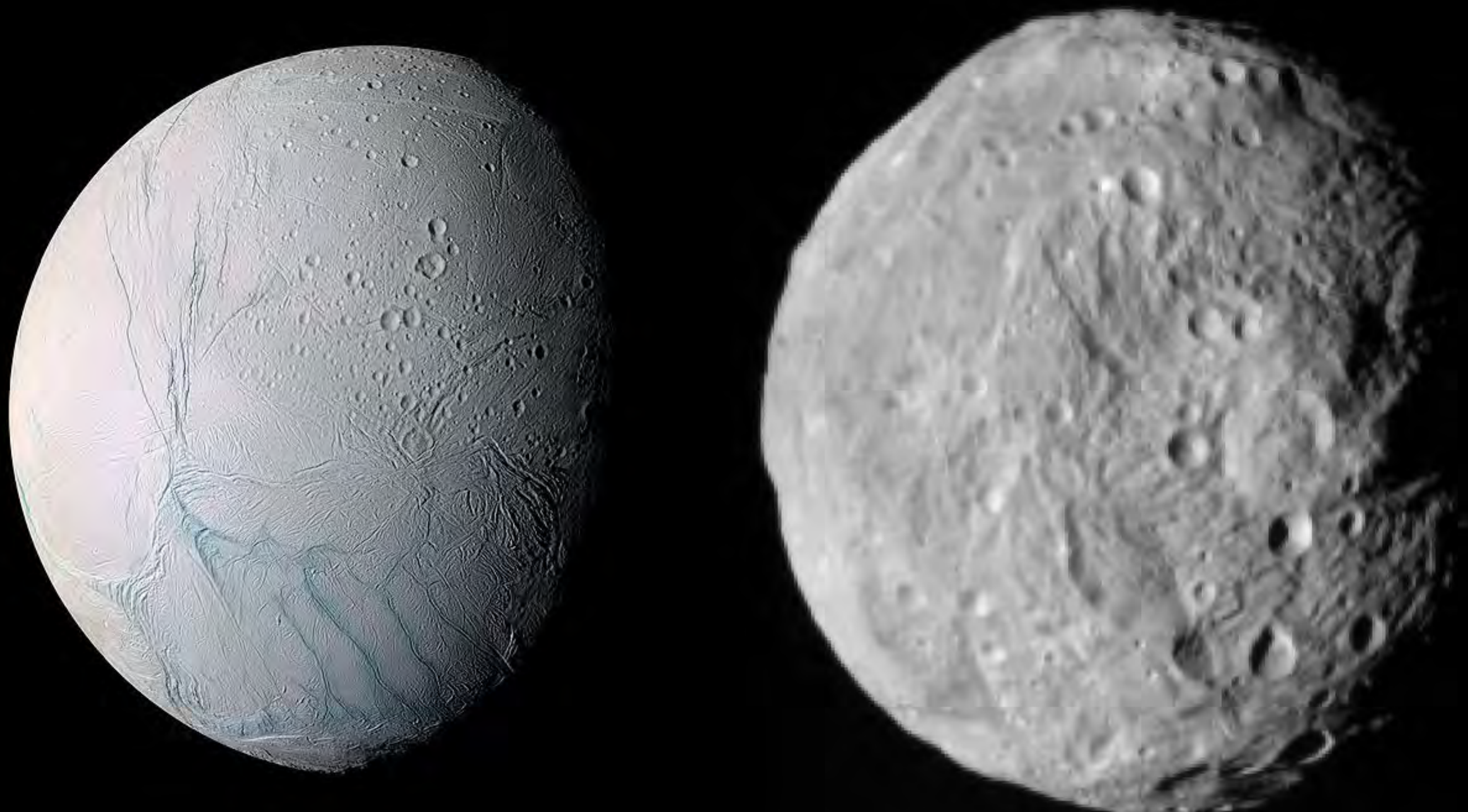

243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
433 Eros - 33 × 13 km
NEAR, 2000
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
951 Gaspra - 18.2 × 10.5 × 8.9 km
Galileo, 1991
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
103P/Hartley 2
2.2 × 0.5 km
Deep Impact/EPOXI, 2010
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
Montage by Emily Lakdawalla of The Planetary Society. Ida, Dactyl, Braille, Annefrank, Gaspra, Borrelly: NASA / JPL / Ted Stryk. Steins: ESA / OSIRIS team. Eros: NASA / JHUAPL. Itokawa: ISAS / JAXA / Emily Lakdawalla. Mathilde: NASA / JHUAPL / Ted Stryk. Lutetia: ESA / OSIRIS team / Emily Lakdawalla. Halley: Russian Academy of Sciences / Ted Stryk. Tempel 1 & Hartley 2: NASA / JPL / UMD. Wild 2: NASA / JPL. Revised 2010-11-16.

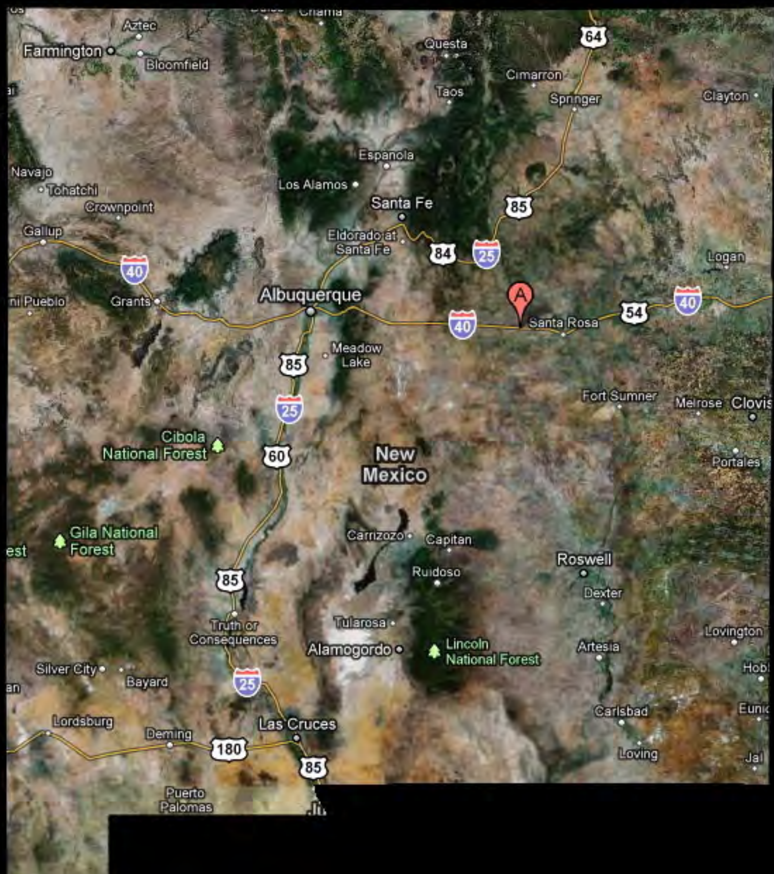


Mars
Mercury
Earth's Moon
Ceres
Vesta

SIZES OF MAJOR ASTEROIDS VISITED

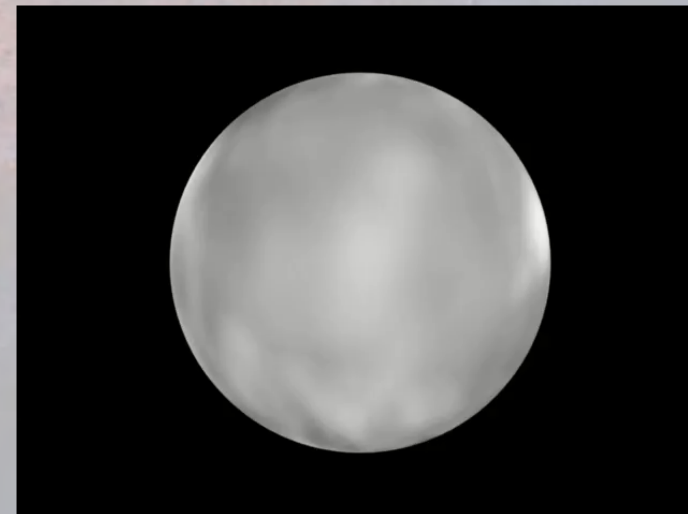


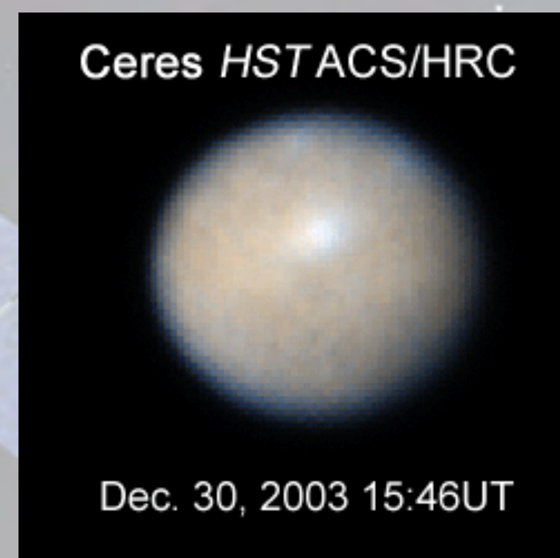



Aztec
Farmington
Bloomfield
Questa
Cimarron
Taos
Springer
Clayton
Espanola
Navajo
Tohatchi
Los Alamos
Crownpoint
Santa Fe
Gallup
Eldorado at Santa Fe
Logan
Grants
Albuquerque
Santa Rosa
Meadow Lake
Fort Sumner
Melrose
Clovis
Cibola National Forest
Portales
New Mexico
Gila National Forest
Carrizozo
Capitan
Roswell
Ruidoso
Dexter
Tularosa
Truth or Consequences
Alamogordo
Lincoln National Forest
Artesia
Lovington
Silver City
Bayard
Lordsburg
Deming
Las Cruces
Carlsbad
Loving
Jal
Puerto Palomas
64
85
84
25
40
54
60
180

Why Ceres ?

- Ceres was the first asteroid discovered
  - ✧ Roughly spherical, w/radius = 468 km
  - ✧ Discovered by Giuseppi Piazzi in 1801
  - ✧ Originally classified as a planet, now a ‘Dwarf planet’
  - ✧ a = 2.766 AU, P_{orb} = 4.6 yr, P_{rot} = 9 hrs
- What is Ceres composed of ?
  - ✧ Ceres is a C type asteroid
  - ✧ Thought to consist of carbonaceous material
  - ✧ Density = 2.21 g/cc
  - ✧ Low porosity, thought to be solid body
  - ✧ Primitive body, spectra indicates H_2O in some form (e.g., phyllosilicates, perhaps ice on surface)
- Ceres was imaged by Hubble
- *Dawn* will arrive at Ceres on March 23, 2015 (± 1 week)

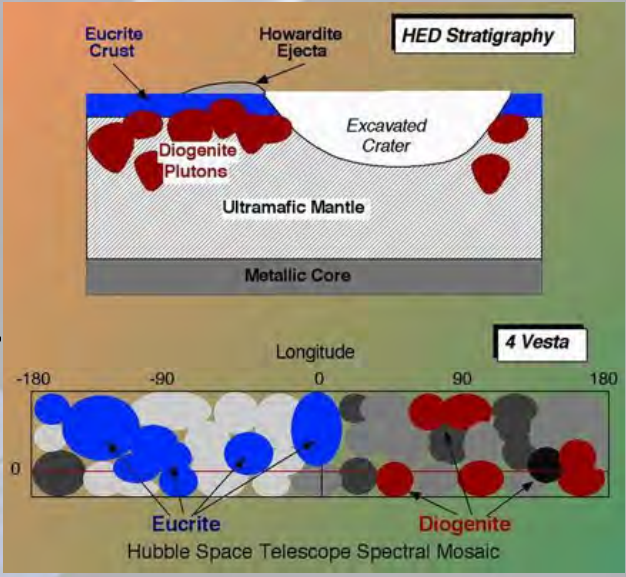




Why Vesta ?

- Vesta was the fourth asteroid discovered
  - ✧ Triaxial ellipsoid, mean radius of 258 ± 12 km
  - ✧ Radii of 289 km x 280 km x 229 km (± 5 km)
  - ✧ Discovered by H. W. Olbers in 1807
  - ✧ $a = 2.36$ AU, $P_{orb} = 3.6$ yr, $P_{rot} = 5.3$ hrs

- What is Vesta composed of ?
  - ✧ Vesta is a V type asteroid or protoplanet
  - ✧ Spectra indicates basaltic minerals (e.g., low-Ca pyroxene, mixtures of plagioclase and pyroxene, Ca-rich augite)
  - ✧ Spectra correlates with HED family of meteorites (Howardite-Eucrite-Diogenite), basaltic achondrites
  - ✧ Basaltic minerals => Volcanic activity once existed
  - ✧ Internal heat => a *differentiated* body
  - ✧ Mass = 2.75-2.99 x 10^{20} kg; volume = 7.19 x 10^{7} km^3
  - ✧ Density = 3.5-3.9 g/cc
  - ✧ Low porosity, thought to be solid body
  - ✧ Spectra indicates no H_2O on surface



- Vesta was imaged by Hubble
- *Dawn* arrived at Vesta on July 16, 2011. How did it get there? Let's look at spaceflight.

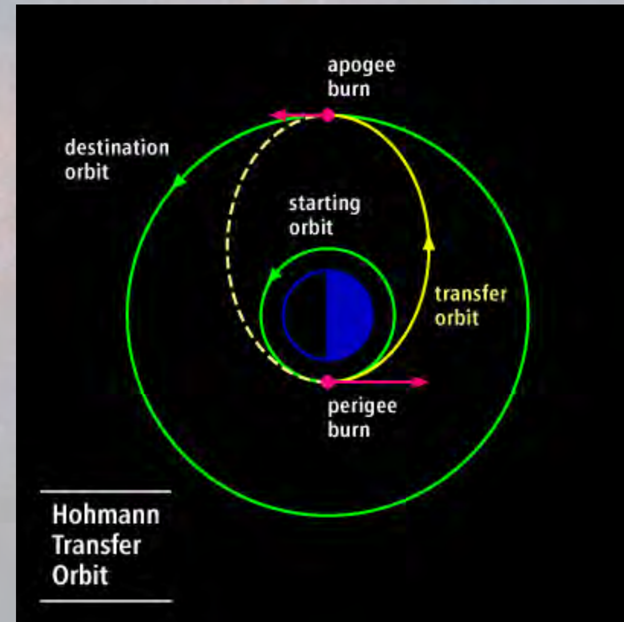
Dawn Launch

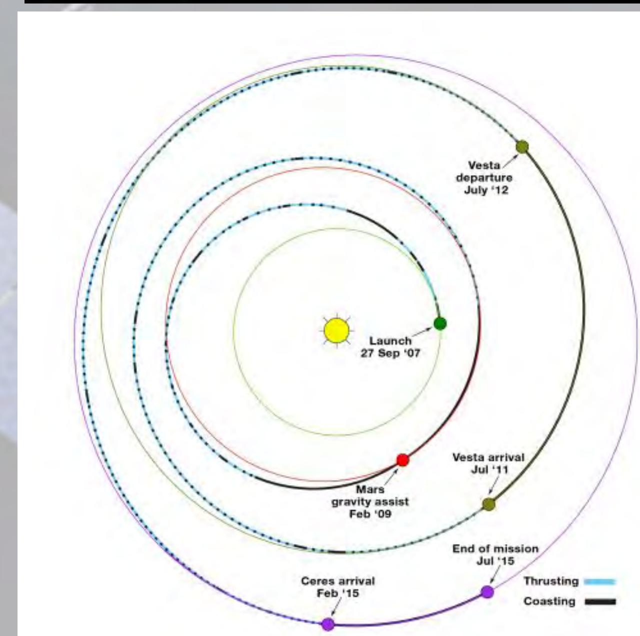
- *Dawn* launched on September 27, 2007

School of Earth & Space Exploration
Arizona State University

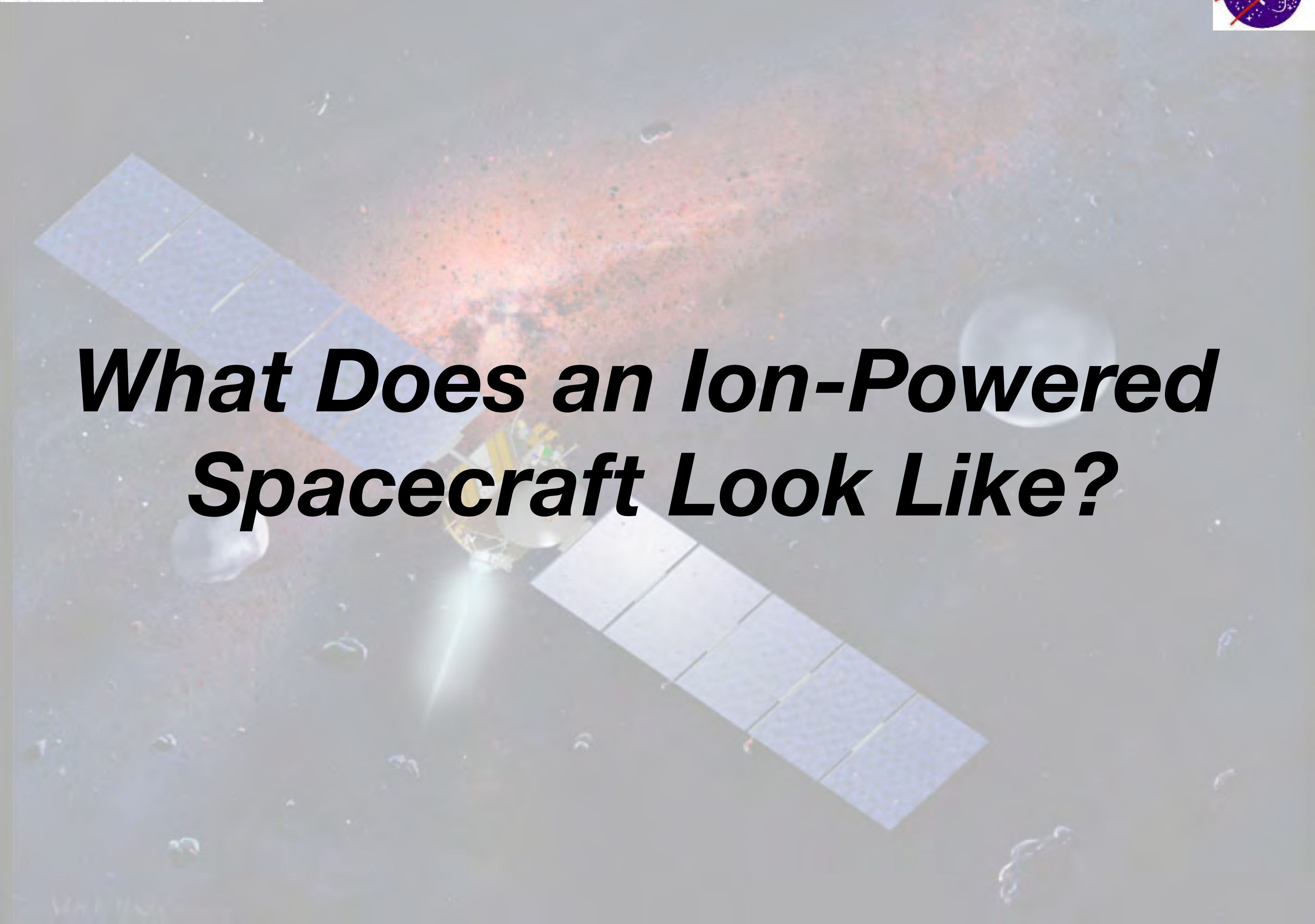
IP: Basics of Spaceflight

- How do most spacecraft travel from Earth to other bodies?
  - Use a Hohmann transfer orbit
  - Increase or decrease ΔV to get to new orbit
  - Gain or loose ΔV with a gravity assist flyby of a planet
- But *Dawn* mission is different. Why?
  - Goal is to orbit two asteroids, Vesta & Ceres
  - *Dawn* is a Discovery-class (small) mission, cost-capped at $466 million
  - To get to Vesta alone, *Dawn* would have require 5400 lbs. of chemical propellants & a larger launch vehicle, making it too $$
  - Instead, want to use new technologies to accomplish science goals of mission
  - Solar-electric ion propulsion space-rated on *Deep Space 1* in 1998-2001, now available for other missions (*Hayabusa*, *SMART-1*, *Rosetta*, *Dawn*)
  - Use *spiraling* orbit with SEP to get there
- Ion propulsion enables the *Dawn* mission



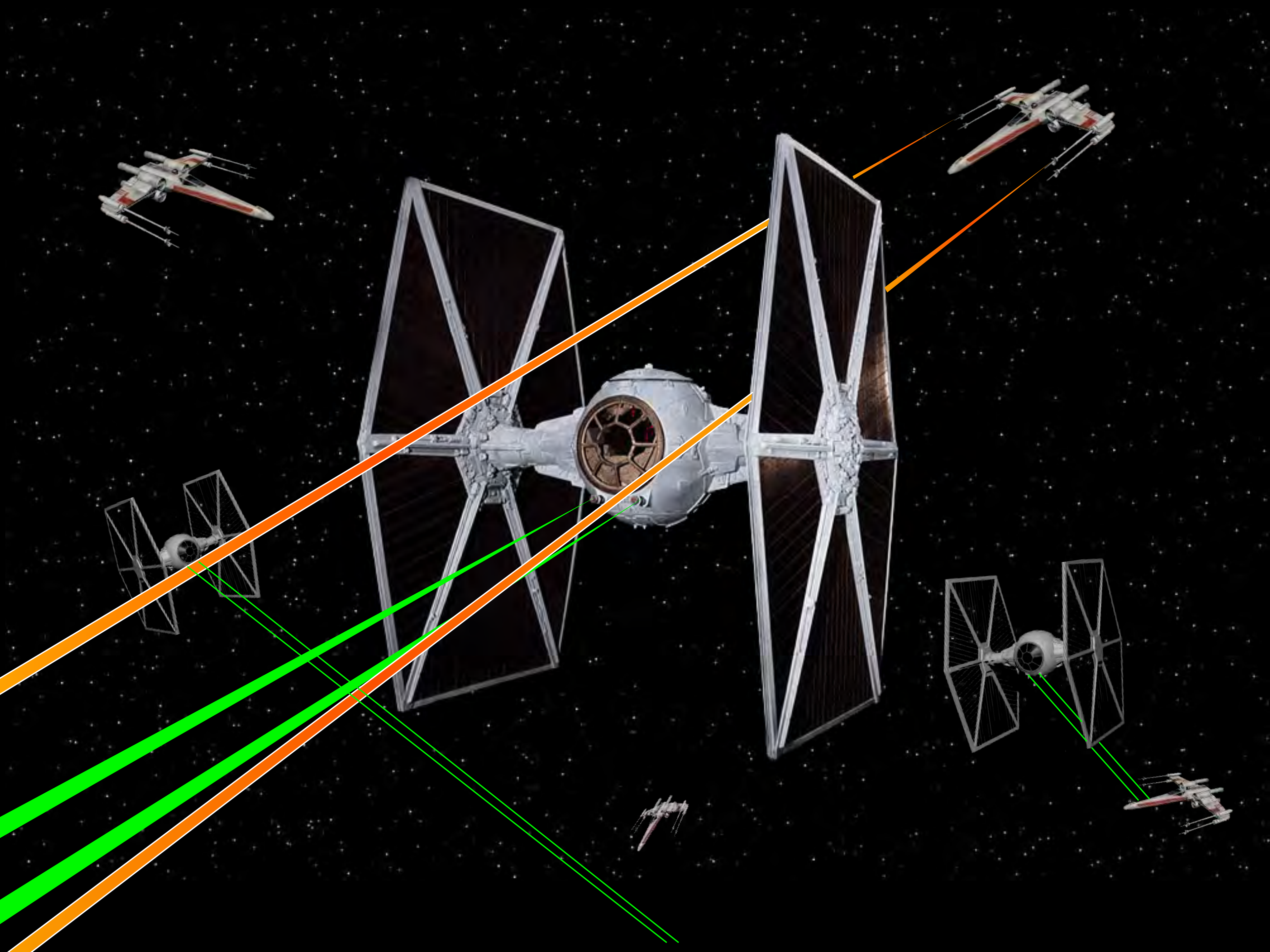


What Does an Ion-Powered Spacecraft Look Like?



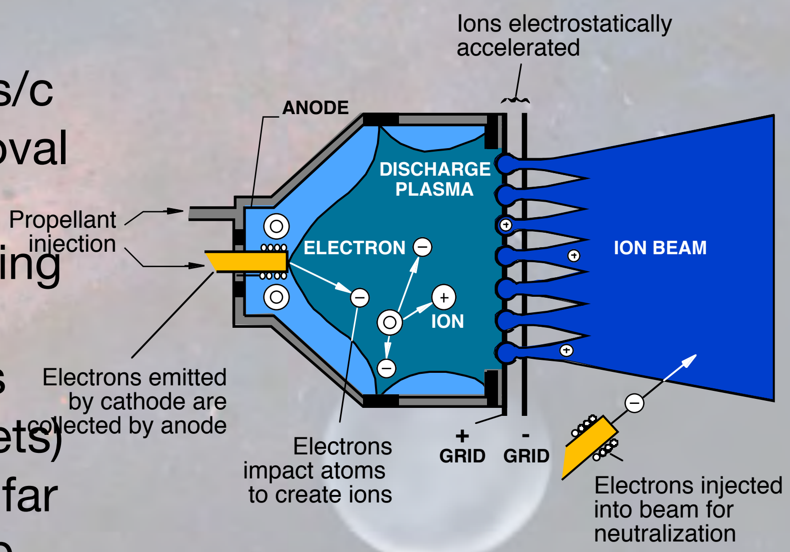


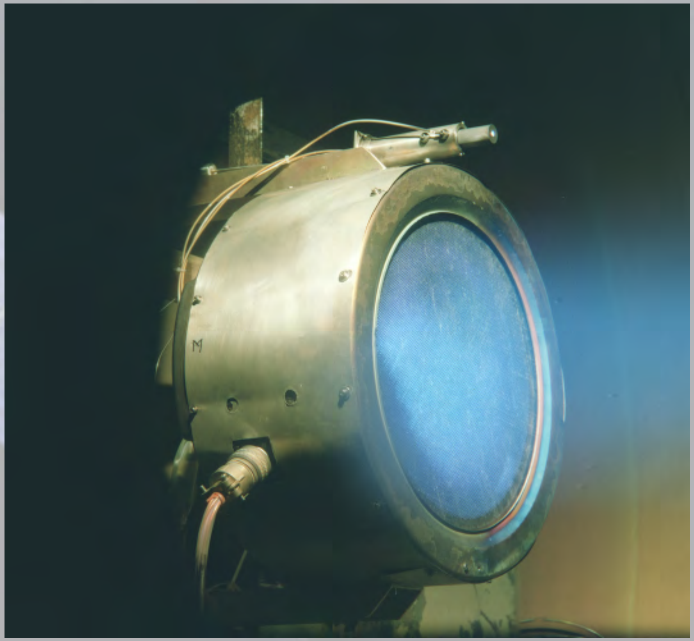


Solar-Electric Ion Propulsion

- How does it work?
  - ✧ Solar panels generate electricity to power s/c
  - ✧ Xenon (Xe), an inert gas, is ionized by removal of 1 electron/atom
  - ✧ 1000 volt electric field is applied, accelerating Xe ions up to 40,000 km/s (89,000 mph)
  - ✧ Reaction force from expelling ion produces propulsion (10x's speed of chemical rockets)
  - ✧ A spacecraft with ion propulsion can carry far less propellant to accomplish the same job as a spacecraft using more standard propulsion
  - ✧ The system uses only about 3.25 mg/s, so 24 hours of continuous thrusting would expend only 10 ounces of Xe
  - ✧ The acceleration is ~7 m/s/day (15 mi/hr/day) i.e., *Dawn* accelerates from 0 to 60 mph in four days
  - ✧ But over 5 years of total thrust time, *Dawn*'s effective ΔV= 11 km/s (> 24,000 mi/hr)
  - ✧ This is the same as an entire 3-stage Delta rocket + 9 SRBs





Comparing Propulsion Systems

- Compare efficiencies of different systems using *specific impulse*
- *Specific Impulse (units: seconds)* is the ratio of the change in momentum due to rock thrust (mass x velocity) per unit of propellant:

$$I_{sp} = \frac{v_e}{g_0}$$

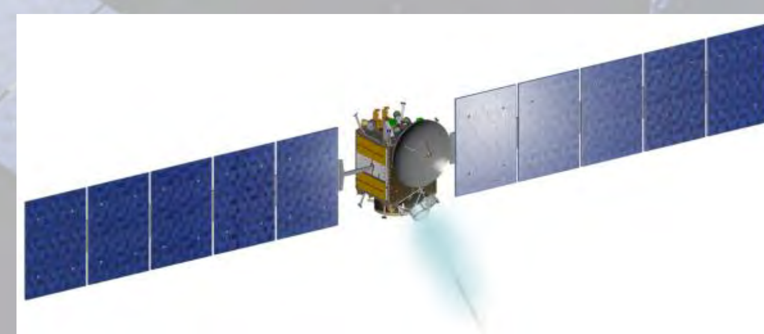
v_e = exit velocity of rocket exhaust (m/s)
g_0 = Earth gravitational acceleration (9.80 m/s^2)

- I_{sp} is the number of seconds an engine can produce its thrust from a given amount of propellant

Engine	S/C	Propellant	Thrust	I_{sp}, sec
RR TVA	*Voyager*	Hydrazine	0.9 N	200
Thiokol Star-37	*Voyager* IPU	Solid Al, NH_4ClO_4	76.5 kN	284
K-M R4-D	*Cassini*	MMH & N_2O_4	445 N	300
Aerojet LR87	Titan III	Aerozine-50 & N_2O_4	1218 kN	302
S Vulcain 2	Ariane 5	Liq H_2 & O_2	1340 kN	434
SSME	Space Shuttle	Liq H_2 & O_2	1670 kN	453
Boeing NSTAR	*Dawn*	Xe ions	0.09 N	3,100

Milestones of *Dawn*' s IP

- Key points about *Dawn*' s power system:
  - ✧ 2 solar arrays, 2.3 x 8.3 m (>7 ft x 27 ft long)
  - ✧ Generate max 10 kW near Earth orbit
  - ✧ *Dawn* consumes 3.2 kW at full throttle
  - ✧ Generate ~4 kW near Vesta orbit
- Key points about *Dawn*' s ion propulsion:
  - ✧ As of 27 May 2011, total of >2.5 yr of ion thrusting, ΔV > 6.5 km/s (14,500 mph)
  - ✧ *Dawn* has traveled 2.7 billion km (1.7 billion miles) since leaving Earth
  - ✧ *Dawn* has expended >216 kg (>51%) of Xe
  - ✧ Expected ΔV = 6.8 km/s at Survey orbit
- Ion propulsion off prior to orbit insertion, called "forced coast"
- *Dawn* approached Vesta from behind, was "captured" into orbit (no or minimal burn required for orbit)

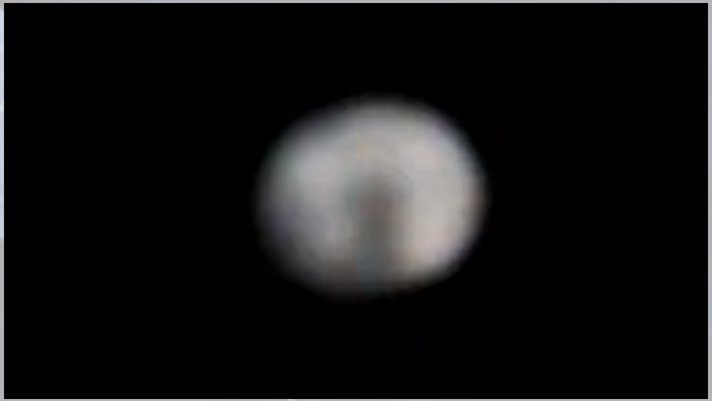


Dawn's Mission "Firsts"

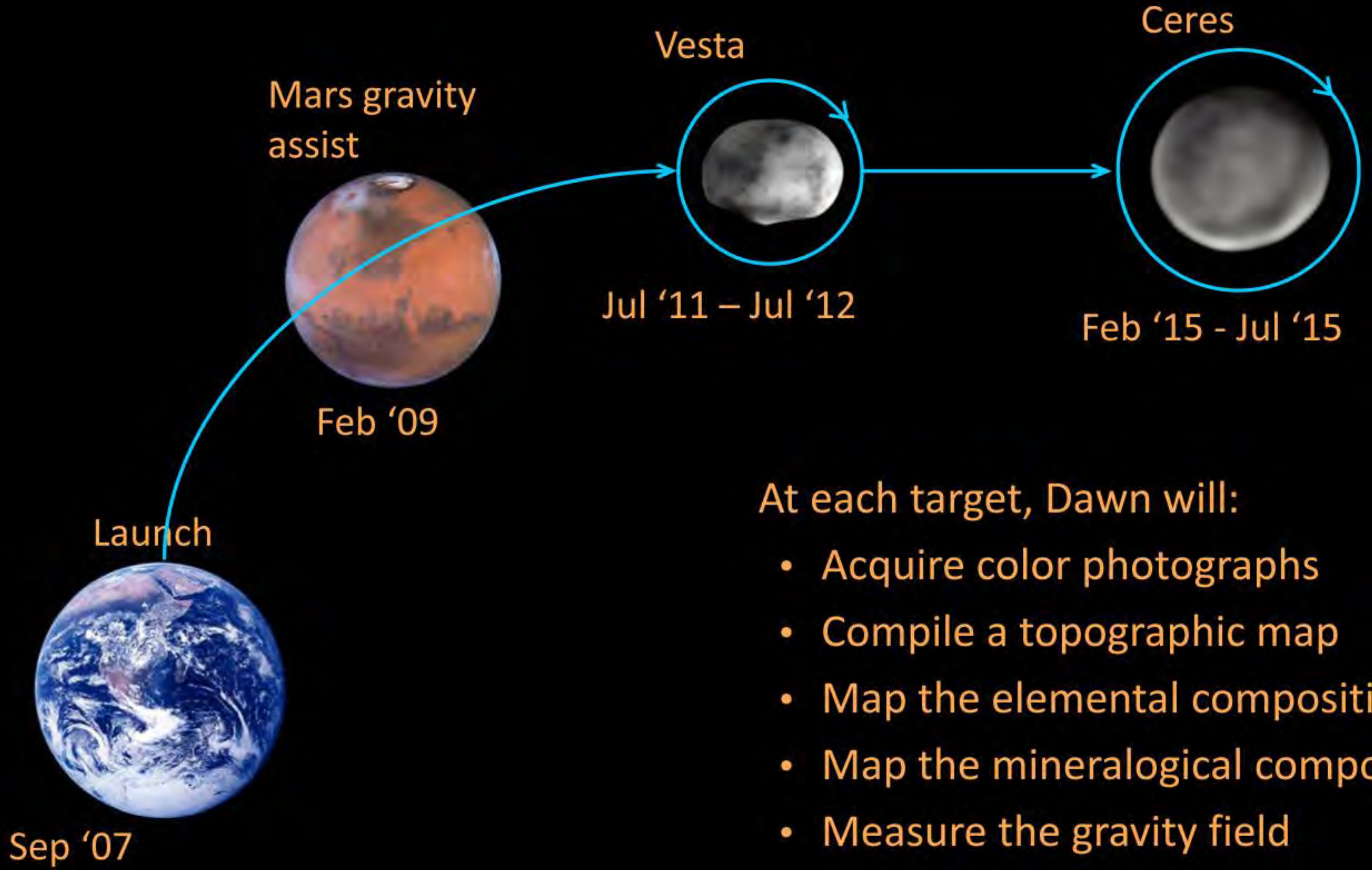
- First mission to Vesta & first to Ceres
- First robot s/c to orbit two SS bodies
- First mission to visit a protoplanet
- First prolonged visit to a main belt asteroid
- First visit to a dwarf planet (Ceres, 2/2015)
- Largest propulsive acceleration of any s/c: Ion engines increased its velocity by 14,300 mph (6.4 km/s) by May 3, 2011 (start of Vesta approach)
- Longest wingspan of any NASA inter-planetary mission launched so far (64 ft, 9 in, or 19.7 m, due to solar panels); *Juno* is larger

NASA *Dawn* Mission

- Objective: What is the role of size and water in determining the evolution of the planets?
  - ✧ Ceres is large & wet
  - ✧ Vesta is smaller & dry
- Three principal scientific drivers for mission:
  - ✧ *Dawn* captures the earliest moments in the origin of the solar system, to understand the conditions under which these objects formed
  - ✧ *Dawn* determines the nature of the building blocks from which the terrestrial planets formed
  - ✧ *Dawn* contrasts the formation and evolution of two small planets that followed very different evolutionary paths so that we understand what controls that evolution



Mission Itinerary



At each target, Dawn will:

- Acquire color photographs
- Compile a topographic map
- Map the elemental composition
- Map the mineralogical composition
- Measure the gravity field

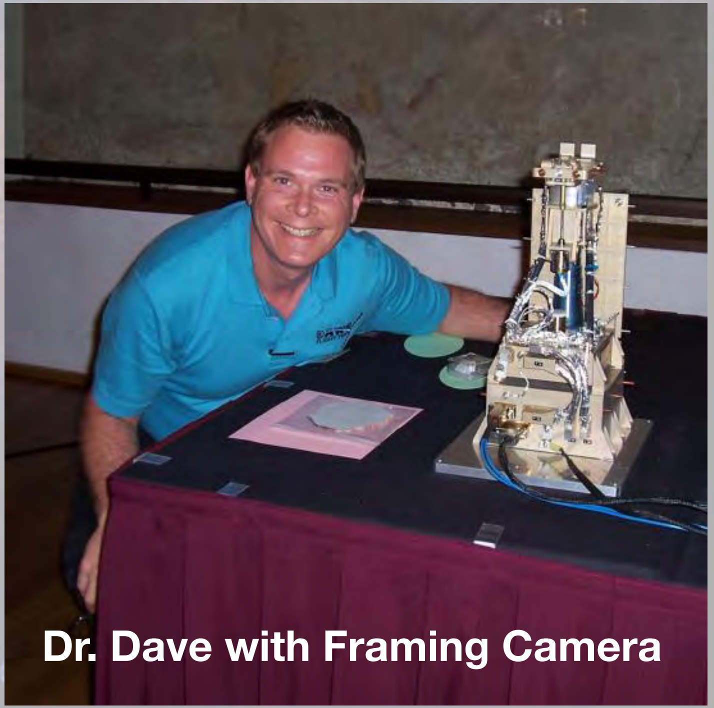
Level I Science Requirement Compliance

Vesta Level 1 Science Requirement	Principal Orbit	Instrument System	Status
Determine the bulk density to 1%	Survey	GRV,FC	Comply
Determine the Spin axis to 0.5 deg	Survey	FC	Comply
Obtain images of 80% of the surface with a resolution of 100 m/pixel in the clear filter and 3 color filters	HAMO	FC	Comply
Obtain a topographic map of 80% of the surface, with horizontal resolution of 100m, and vertical resolution of 10 m	HAMO	FC	Comply
Obtain 10,000 spectral frames at wavelengths of 0.25 – 5 μm with a spectral resolution of 10 nm (to measure and map the mineral composition). At least half of these spectral frames will be at a spatial resolution ≤ 200 m, with the rest at a spatial resolution ≤ 800 m.	Survey, HAMO	VIR	Comply
Measure and map the abundances of the major rock forming elements to 20% precision with a resolution ~1.5 times the mapping altitude over the entire surface to ~1m depth	LAMO	GRaND	Comply
Measure and map the abundances of H, K, Th, and U over the entire surface to ~1 meter depth	LAMO	GRaND	Comply
Determine the gravity field with a half-wavelength resolution of 90 km	LAMO	GRV	Comply

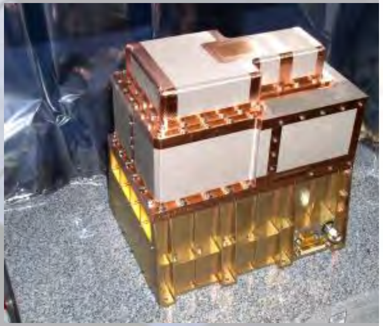
Notes:
- These are not the formal statements of the success criteria
- The success criteria for Ceres are similar

Instruments

- Three remote sensing instruments
  - ✧ Framing Camera (FC): German
  - ✧ Visible & Infrared Spectrometer (VIR): Italian
  - ✧ Gamma Ray & Neutron Detector (GRaND): USA
- FC: MPS, DLR
  - ✧ Images surface for morphology, albedo, color
  - ✧ Determines topography via stereo imaging & production of digital terrain models (DEMs)
- VIR: INAF, ASI
  - ✧ Measures reflected sunlight and emitted thermal radiation (850 spectral bands 0.2-5 μm)
  - ✧ Extract mineralogical signatures & thermal properties of surface materials
- GRaND: Los Alamos NL, PSI
  - ✧ Measures elemental abundances of surfaces
  - ✧ Helps derive compositions of surface
- Gravity Science Experiment: USA
  - ✧ Assess gravity of body via variation of radio signals; derives gravitational field



Dr. Dave with Framing Camera

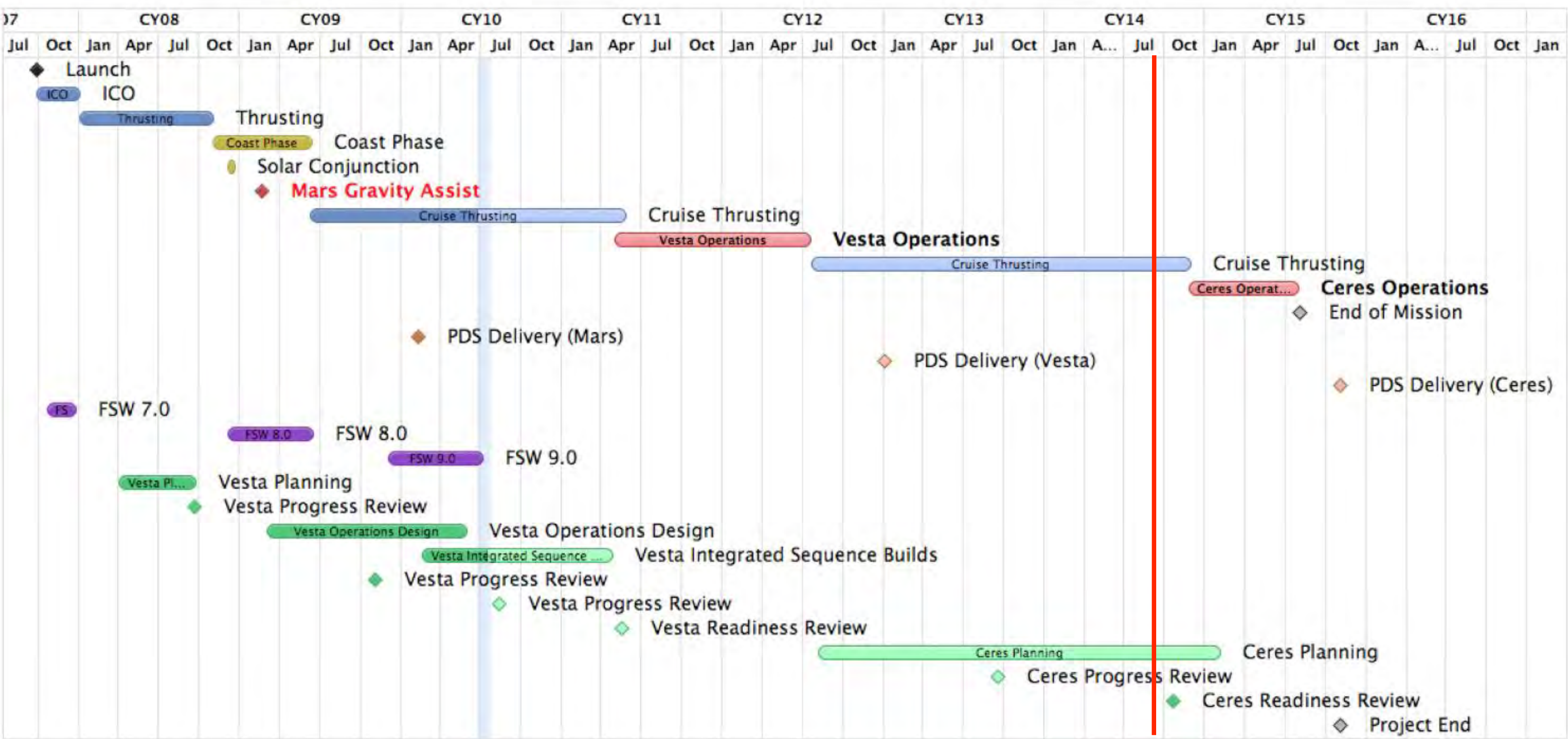


GRaND

VIR

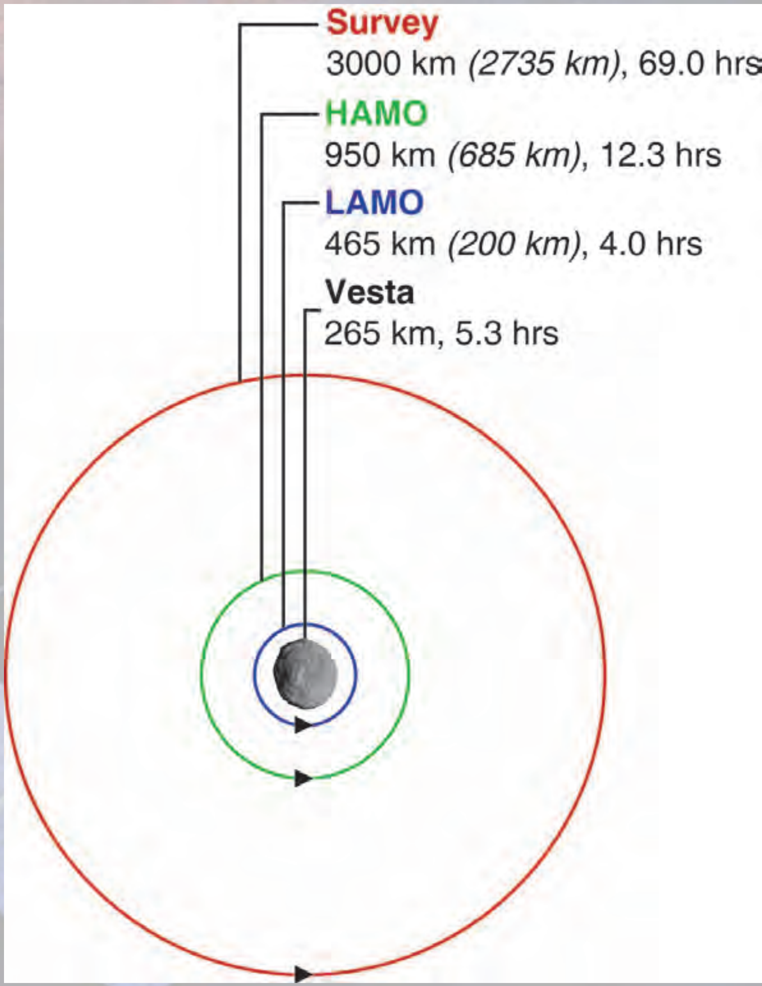
Operations: Timeline

- *Dawn* ‘captured’ into Vesta orbit 16 July 2011
  - *Approach:* May-Aug 7, 2011;
  - *Survey* orbit: Aug 11-30, 2011
  - *HAMO-1* orbit: Sep 30- Oct 30, 2011
  - *LAMO* orbit: Dec 12, 2011–Apr 30, 2012
  - Ops Margin: Feb 8 – Apr 7, 2012
  - *HAMO-2* orbit: Jun 19 – Jul 25, 2012
  - *Departure*: Sep 5, 2012

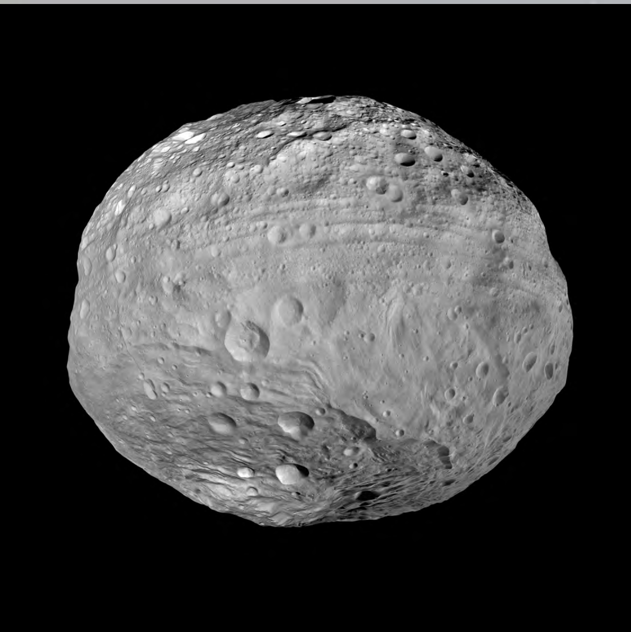


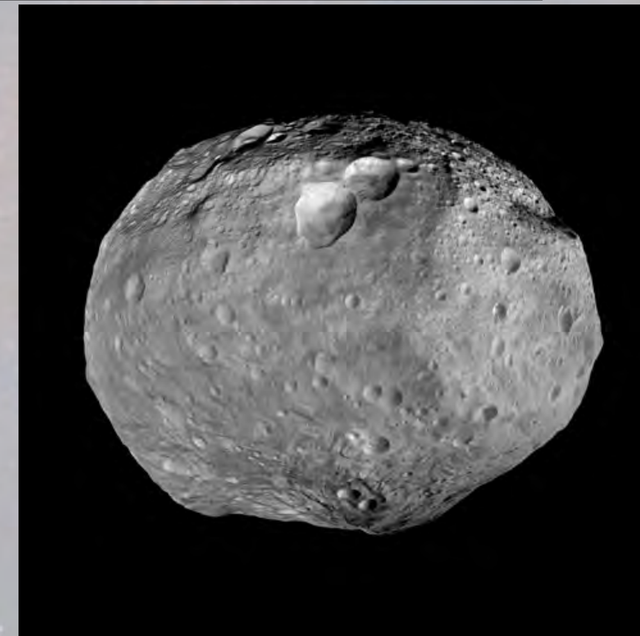
Operations: Orbits

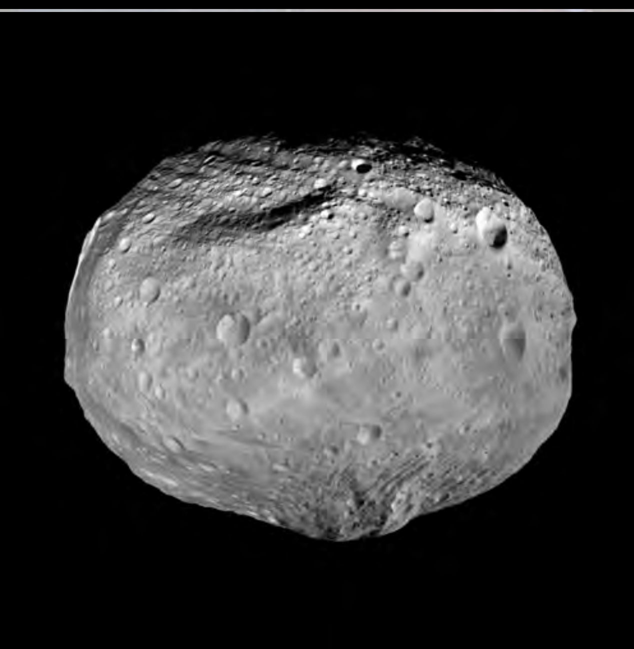
- *Approach:* FC resolution: 10 km/px to 470 m/px
  - Gradually better than Hubble ST resolution
  - Goal: Search for Vestan moons
  - Verify safety for close orbits
- *Survey* Orbit:
  - FC resolution: 200 m/px; VIR res: 800 m/px
  - Global assessment of surface feature types
  - Identify large features, areas for detailed study
- *High-Altitude Mapping Orbit-1* (HAMO-1):
  - FC resolution: 70 m/px
  - Identify & map Vesta at regional scale
  - Focus on south pole crater, southern hemisphere to mid latitudes
- *Low-Altitude Mapping Orbit* (LAMO):
  - FC resolution: 20-25 m/px
  - Identify & map Vesta at local scale
- *HAMO-2* Orbit:
  - FC resolution: 70 m/px
  - Identify & map Vesta at regional scale
  - Focus on mid- to northern latitudes

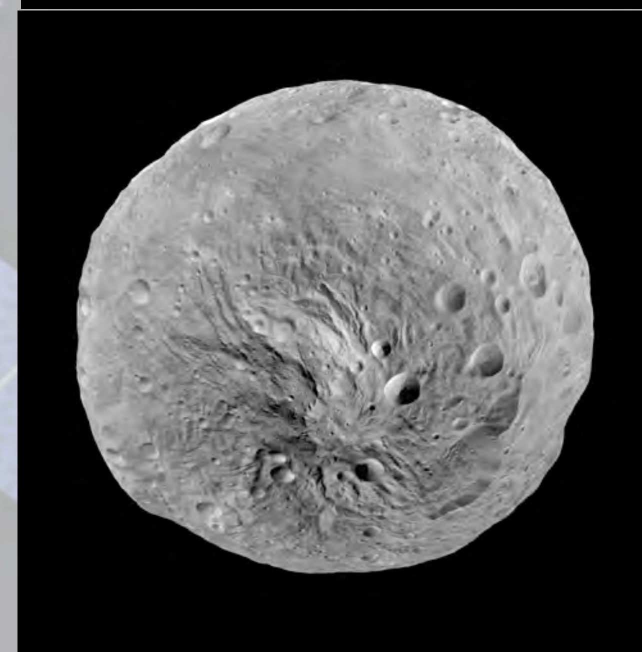


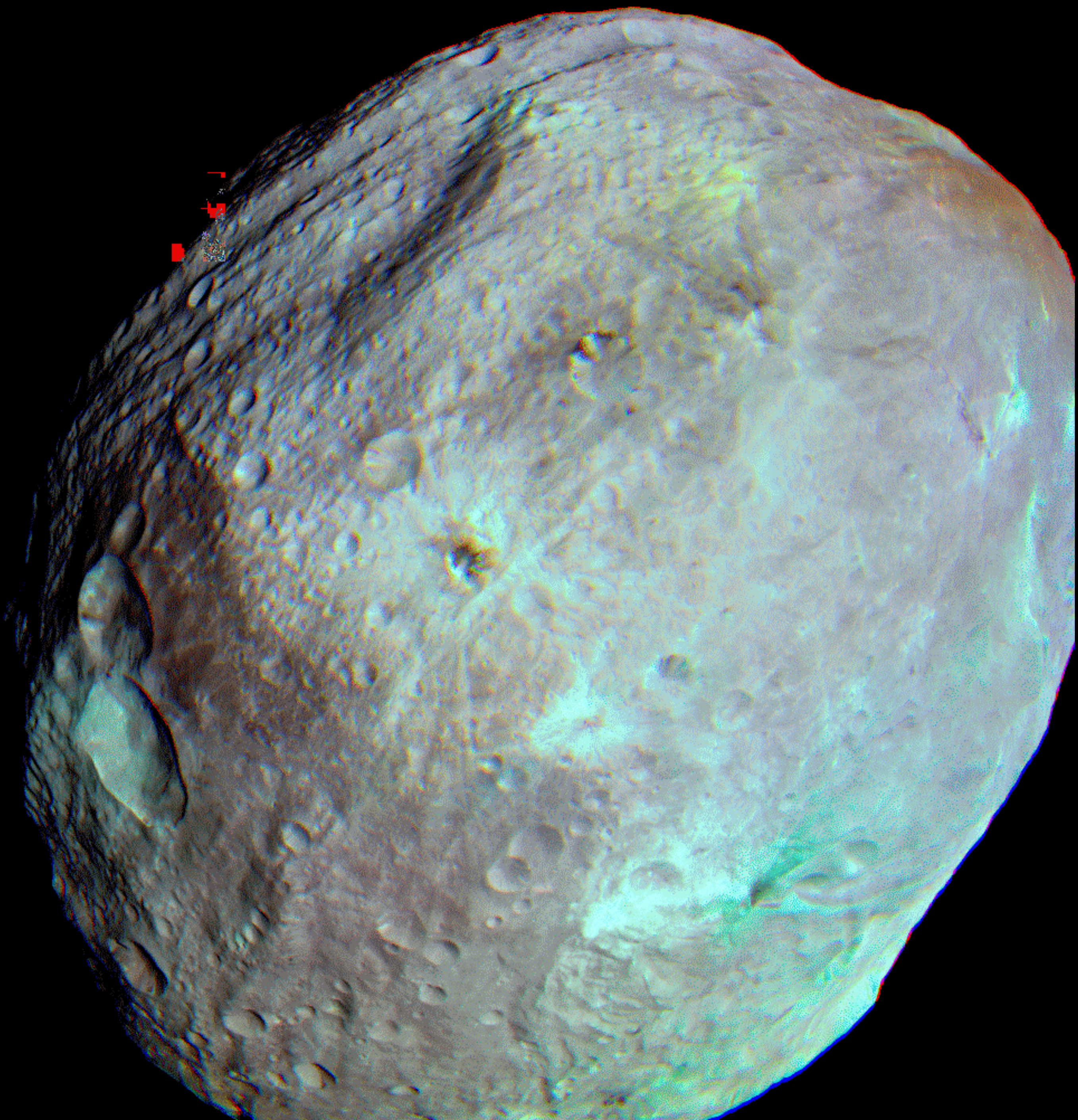
Approach (Rotation Characterization)











First Published Results!

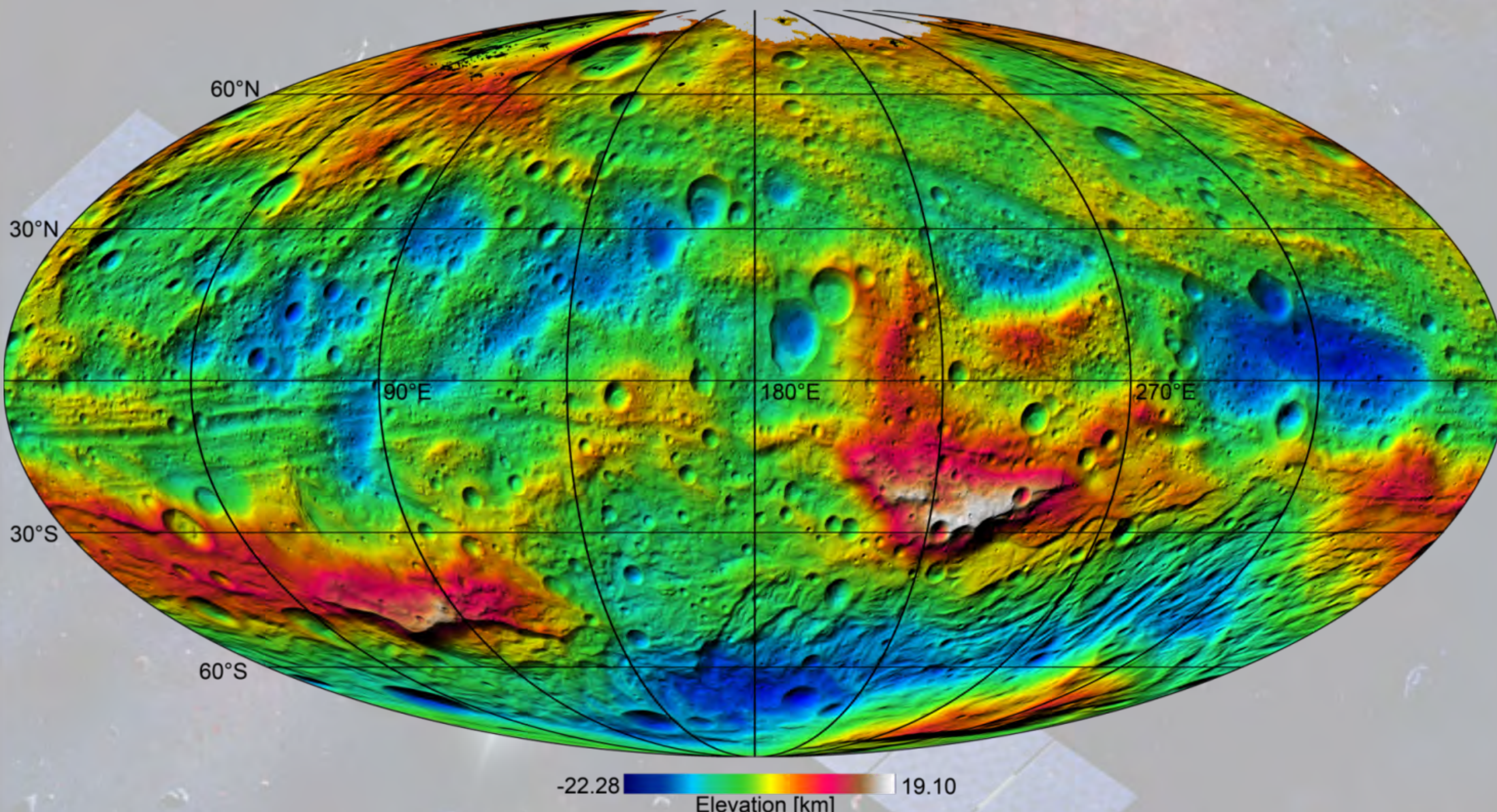
- Six papers, May 11, 2012 issue of *Science*
  - ✧ Vesta as a Protoplanet
  - ✧ Vesta's Shape and Morphology**
  - ✧ Violent Colisional History of Vesta
  - ✧ Recent Giant Impact Basins**
  - ✧ Mineralogy & its Diversity
  - ✧ Color and Albedo Variations
- Vesta is the source of HEDs
  - ✧ Compositional varitions consistent with HED mineralogy
  - ✧ Gravity signature shows Vesta has a core; impacts excavated mantle
- Two large basins confirmed at south pole
- Surface geology dominated by impact-related processes

Recent Papers

- *Buczkowski et al*., Vesta's troughs, *Geophys. Res. Lett*., Sep 29, 2012
- *Reddy et al*., Dark material on Vesta delivered by CC meteorites, *Icarus*, Nov-Dec, 2012
- Two papers, Oct 12, 2012 issue of *Science*
  - ✧ First GRaND results
  - ✧ Pitted terrain – evidence of volatiles
- Two papers, Nov 1, 2012 issue of *Nature*
  - ✧ Vesta's bright & dark material
  - ✧ Vesta's space weathering
- Several special issues of planetary science journal now published or in progress

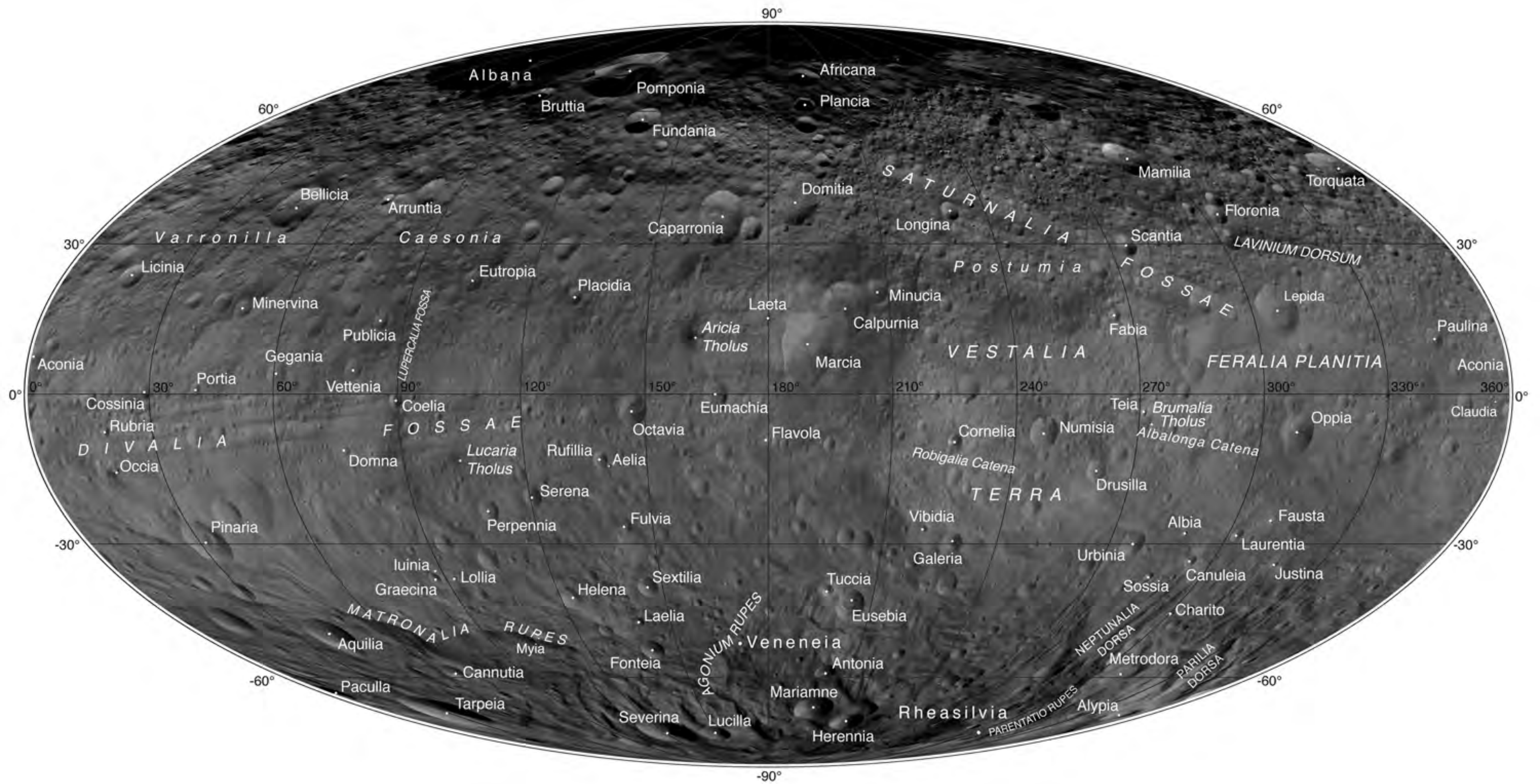
Vesta's Geology

Vesta's Topography



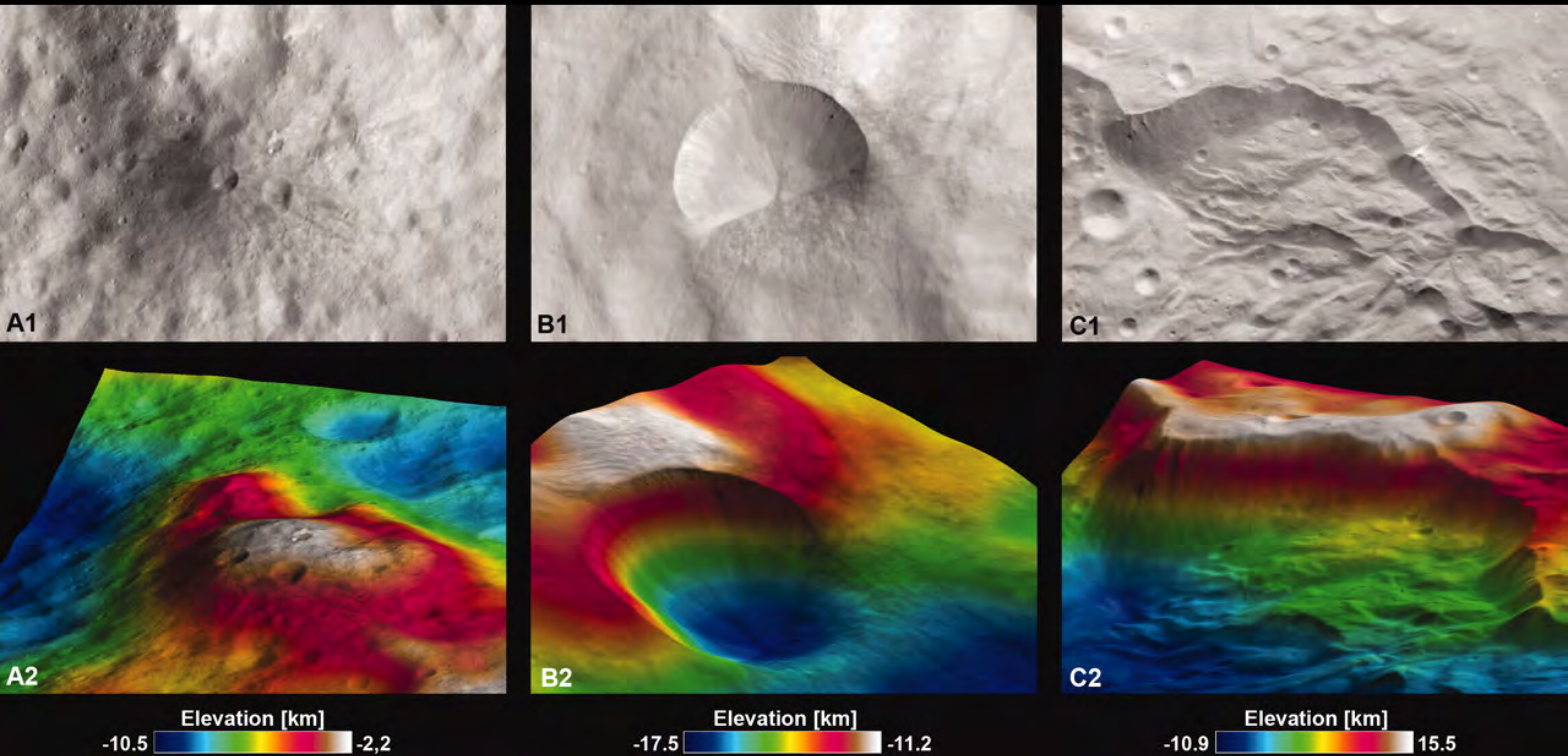
The topography to radius relation on Vesta amounts to $\Delta R_{topo}/R$ ~30% (Moon and Mars yield 1%) This makes Vesta a hilly and slope-intensive environment.

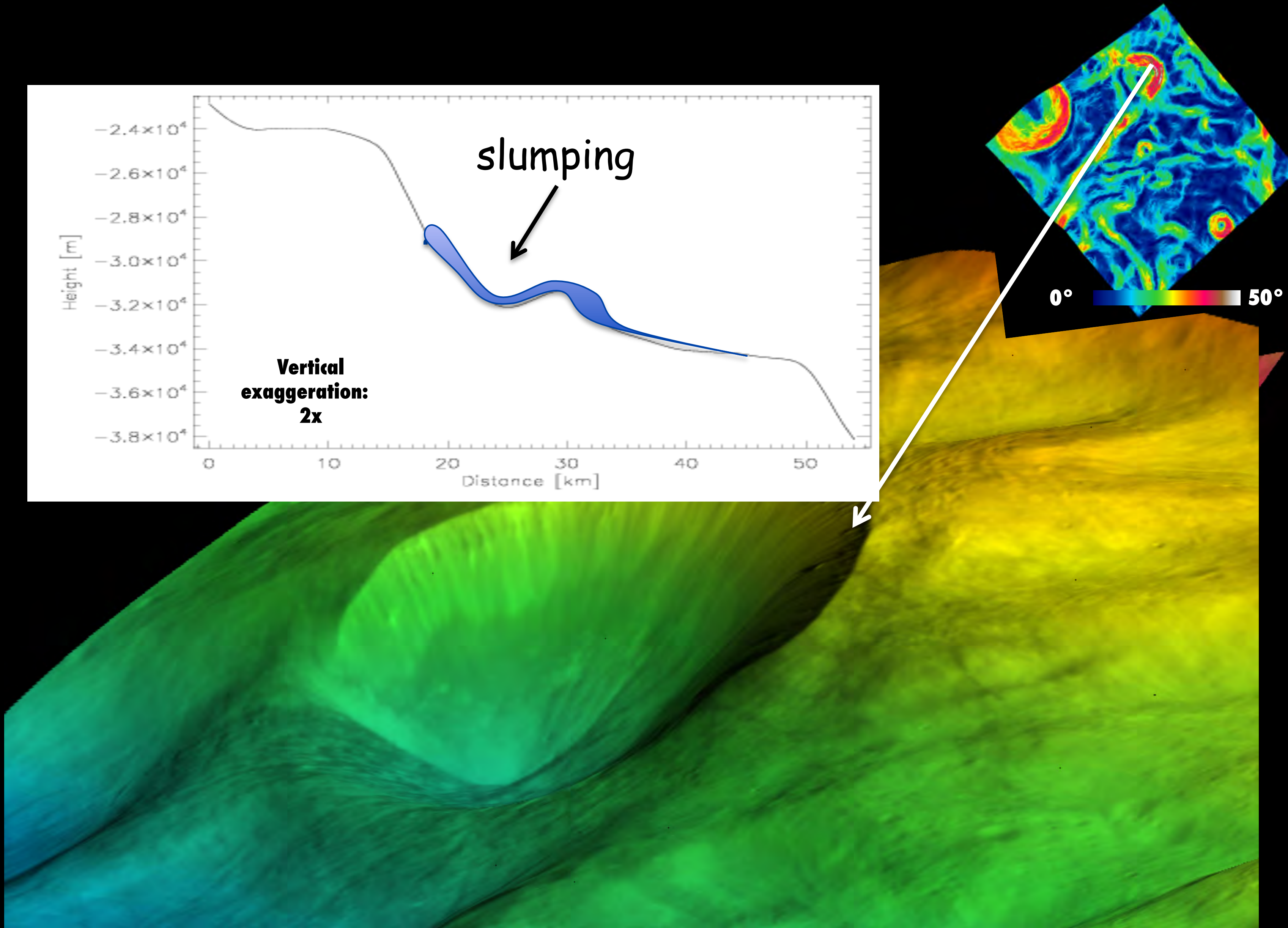
Vesta Nomenclature



Key Geology Results:

- Impact cratering is the dominant geologic process that has modified Vesta's surface
- Vesta's extensive steep slopes results in many mass wasting deposits, & 'bimodal crater' (sharp rim upslope, subdued rim downslope)
- Any evidence of Vesta's ancient volcanism has been destroyed



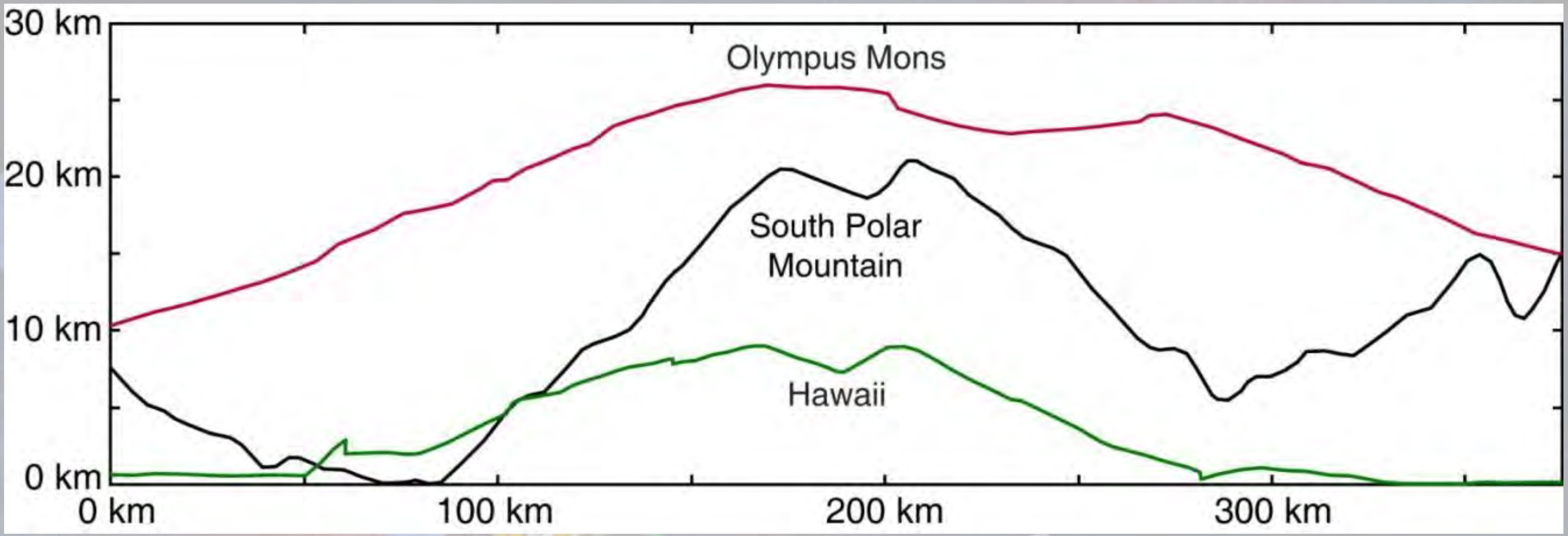


slumping
Height [m]
−2.4×10⁴
−2.6×10⁴
−2.8×10⁴
−3.0×10⁴
−3.2×10⁴
−3.4×10⁴
−3.6×10⁴
−3.8×10⁴
0
10
20
30
40
50
Distance [km]
Vertical exaggeration: 2x
0°
50°

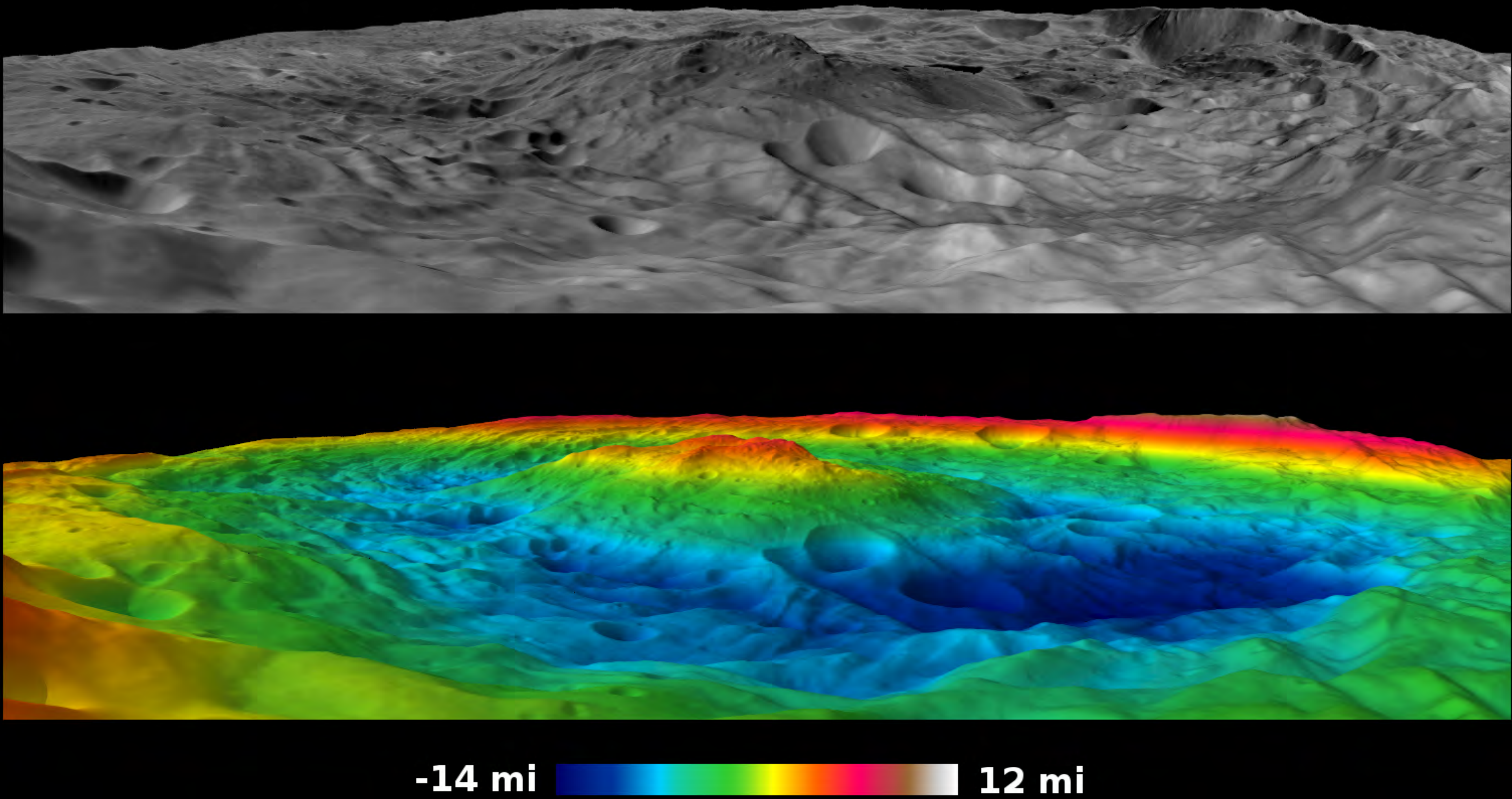
pes

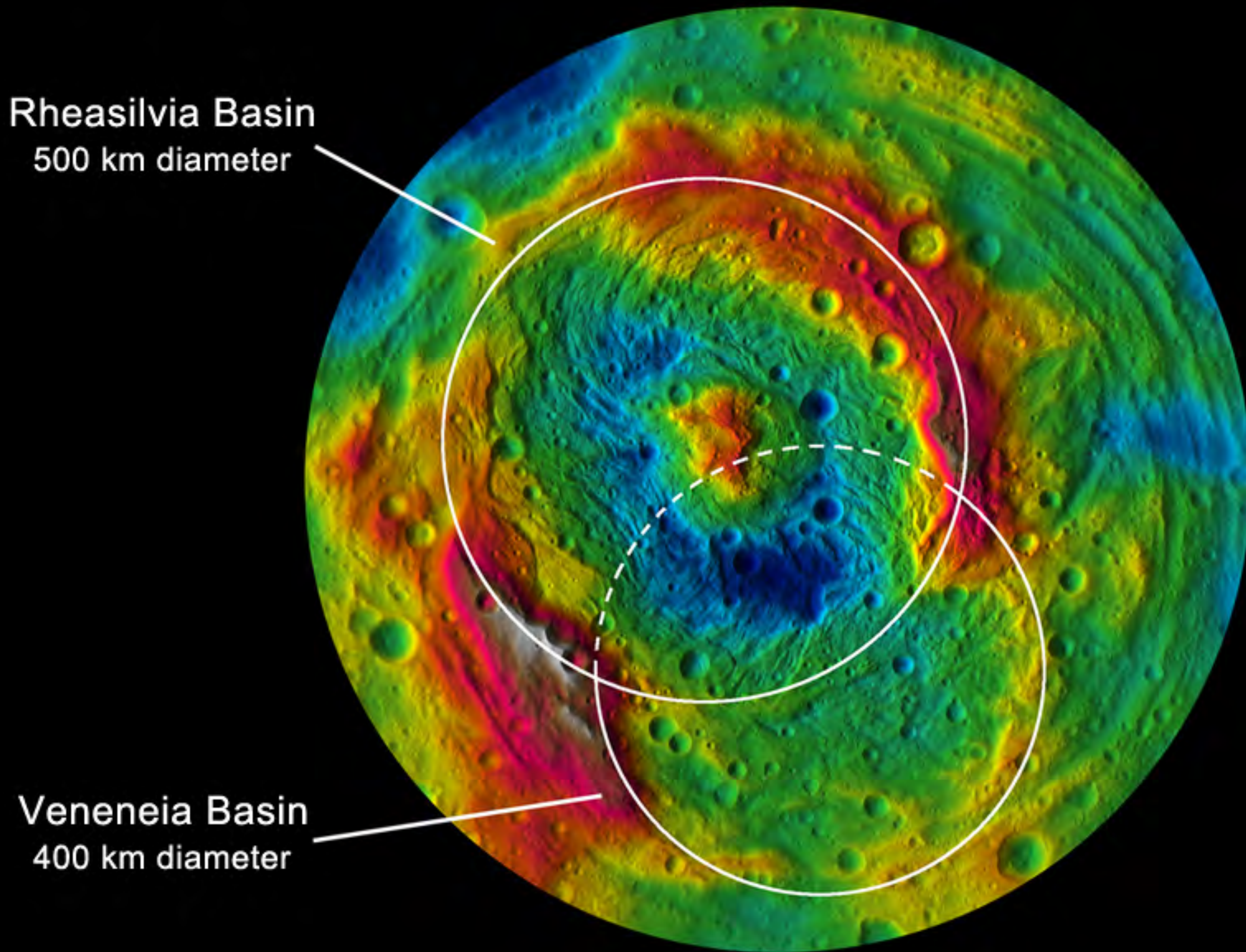
ai

South Polar Mountain

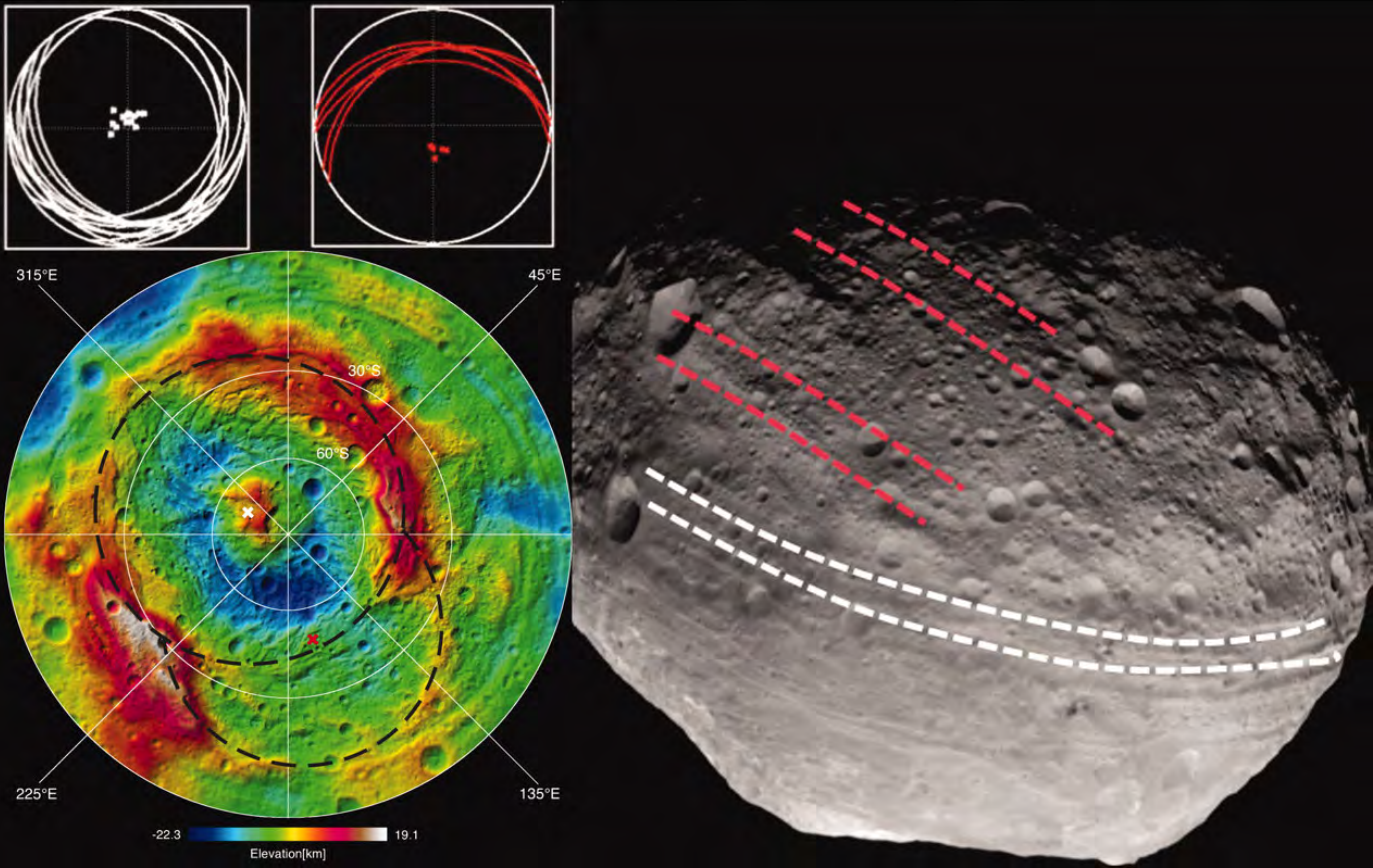


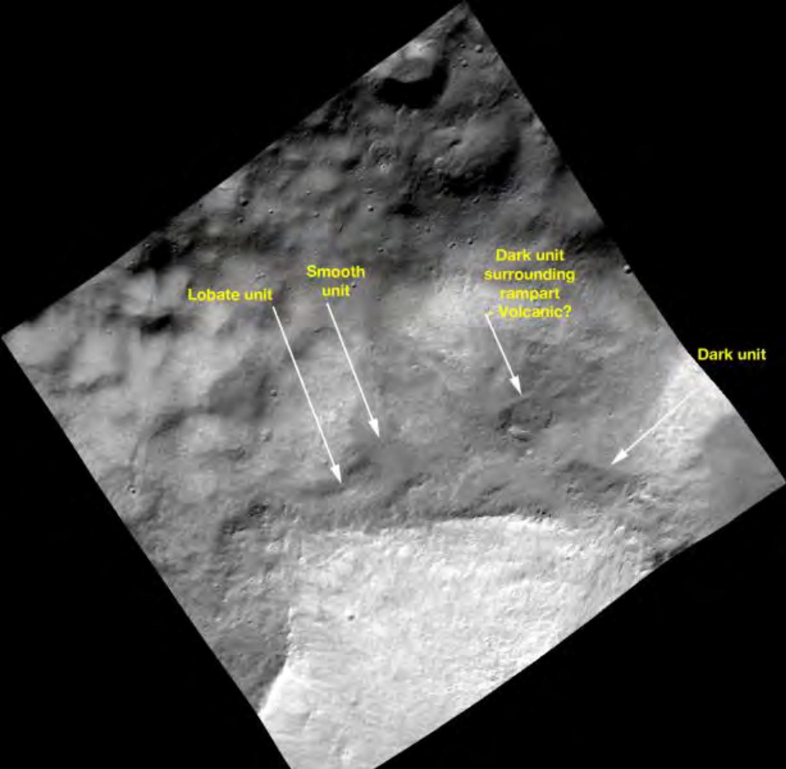
- This slide compares in absolute units the height and width of the south pole mountain with Mars' Olympus Mons, the solar system's largest volcano.
- This mountain is comparable in height to Olympus Mons.
- It dwarfs any mountain on Earth.
- It is the central peak of the 505-km diameter Rheasilvia basin.

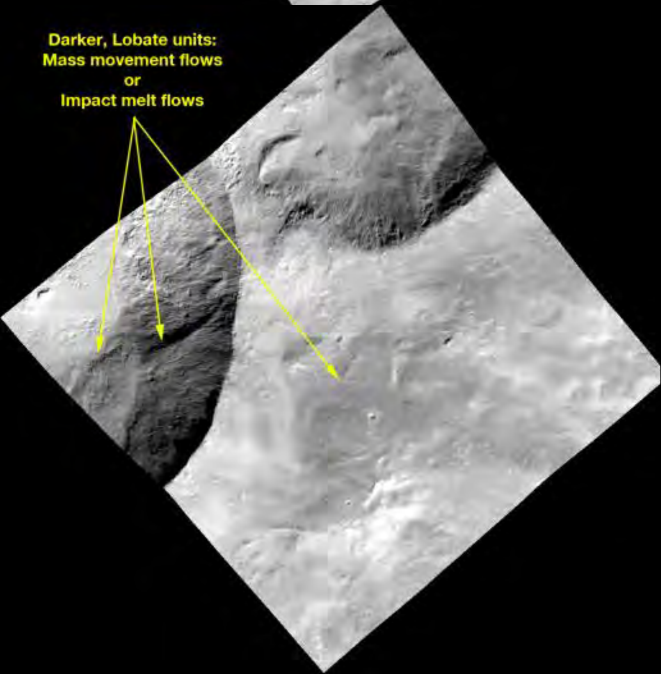

-14 mi
12 mi

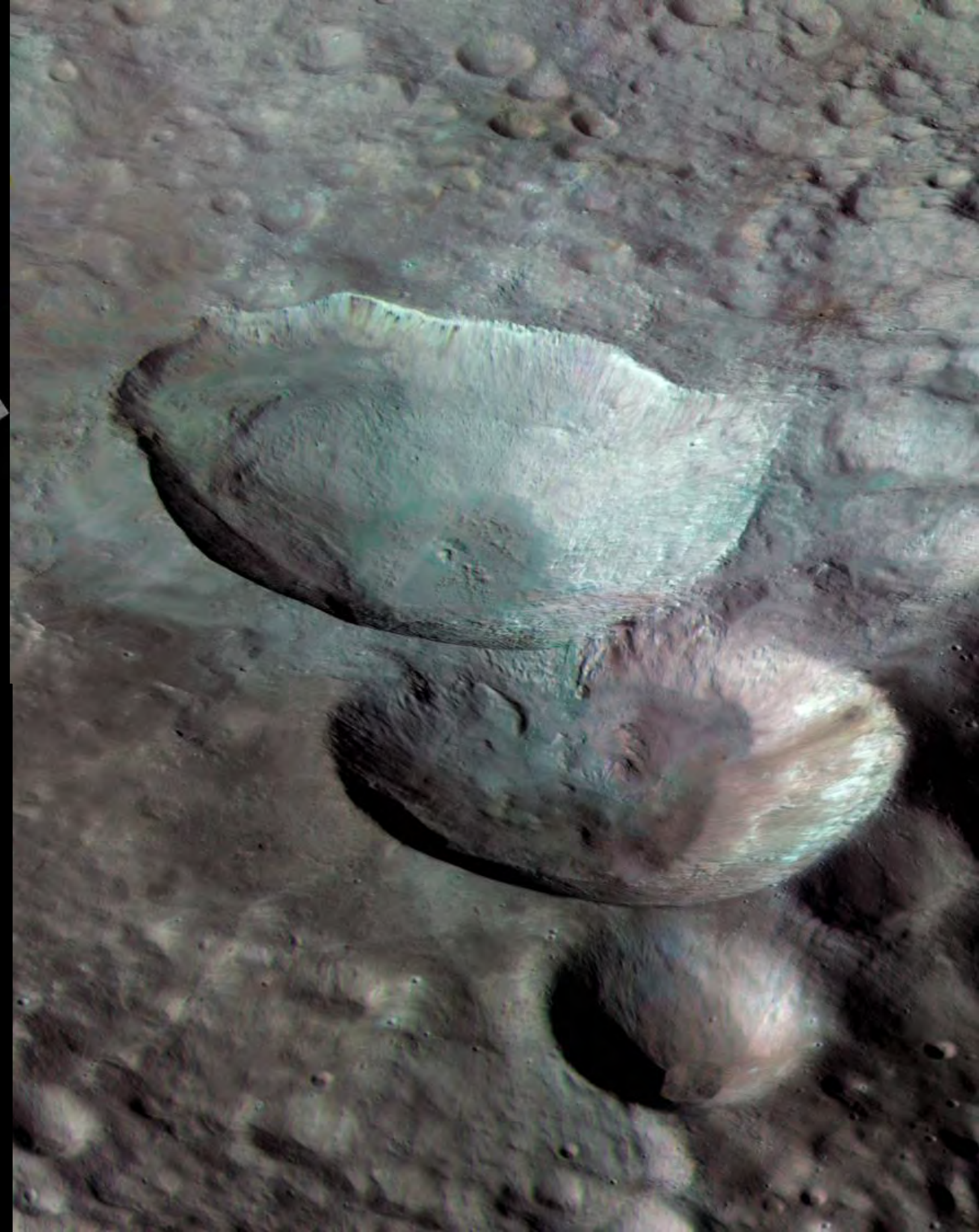

Rheasilvia Basin
500 km diameter
Veneneia Basin
400 km diameter

Vesta's troughs are a tectonic response to impact basin formation



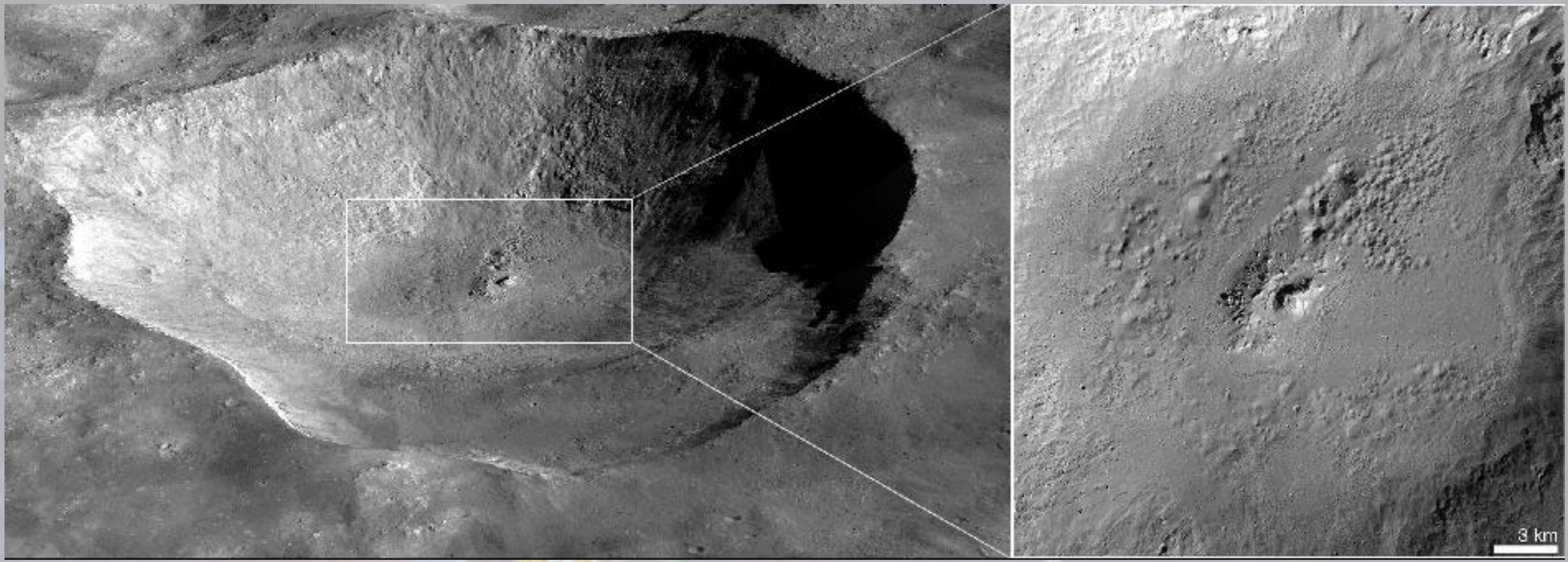

Lobate unit
Smooth unit
Dark unit surrounding rampart - Volcanic?
Dark unit


Darker, Lobate units:
Mass movement flows
or
Impact melt flows

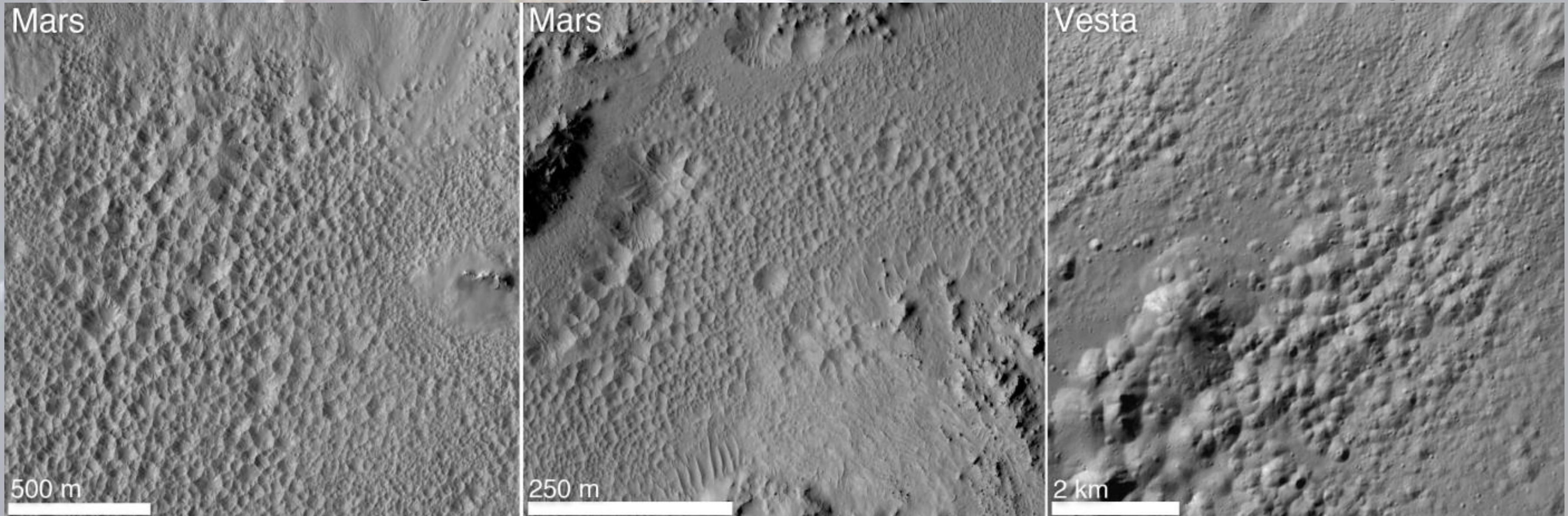


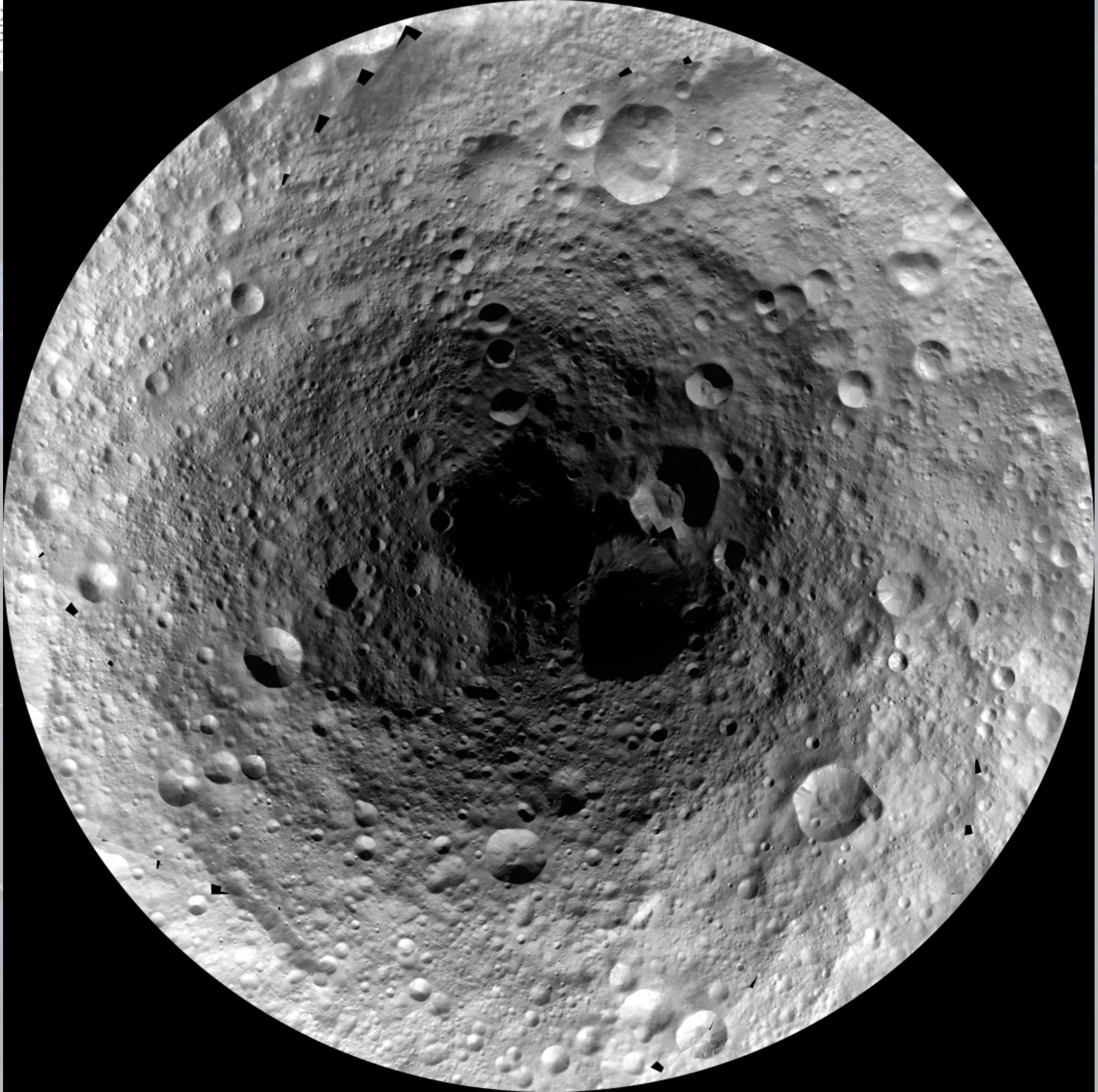
Pitted Terrain

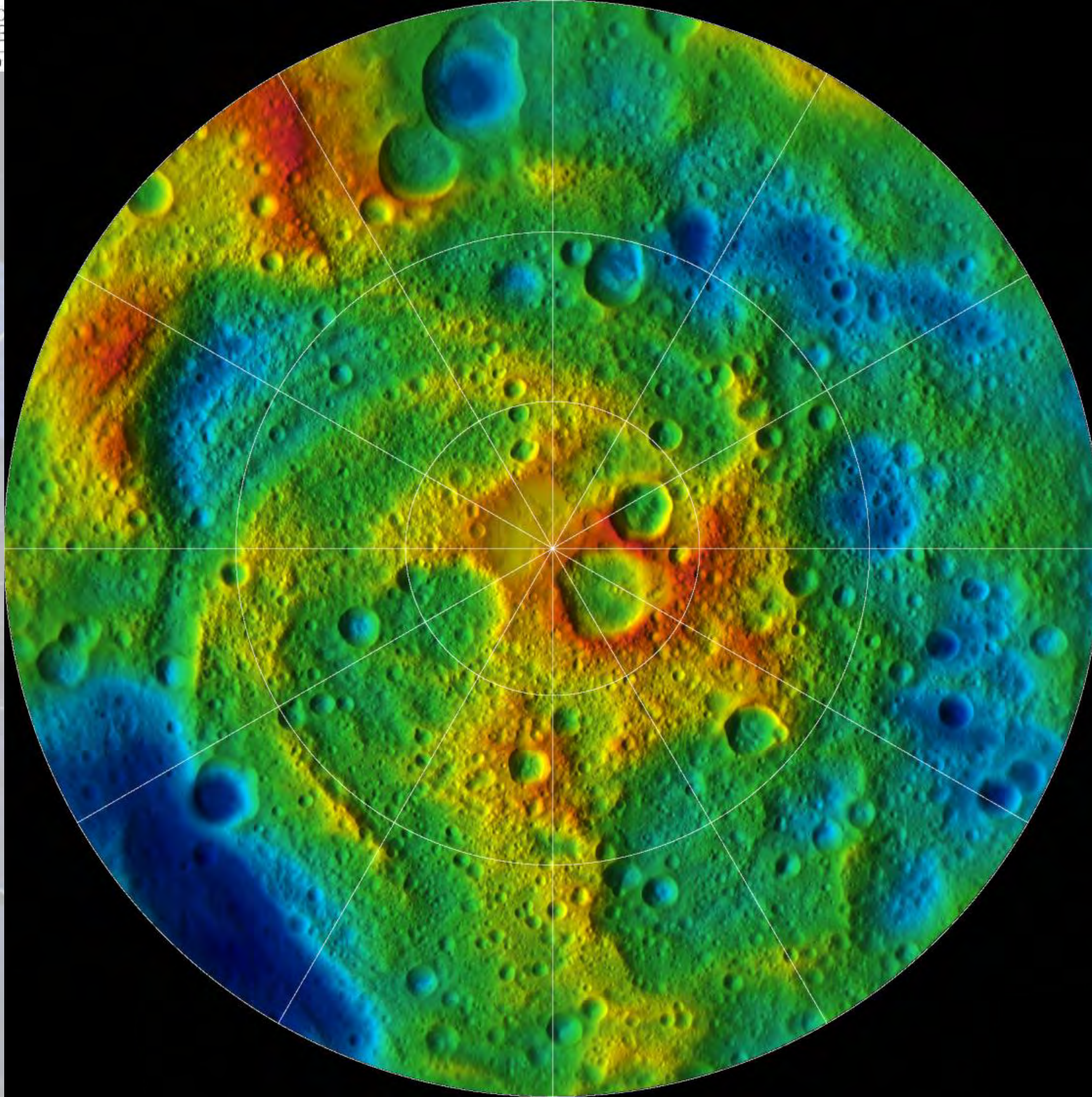
Denevi et al., 2012, Science



Formation through devolatilization of subsurface or cometary ice







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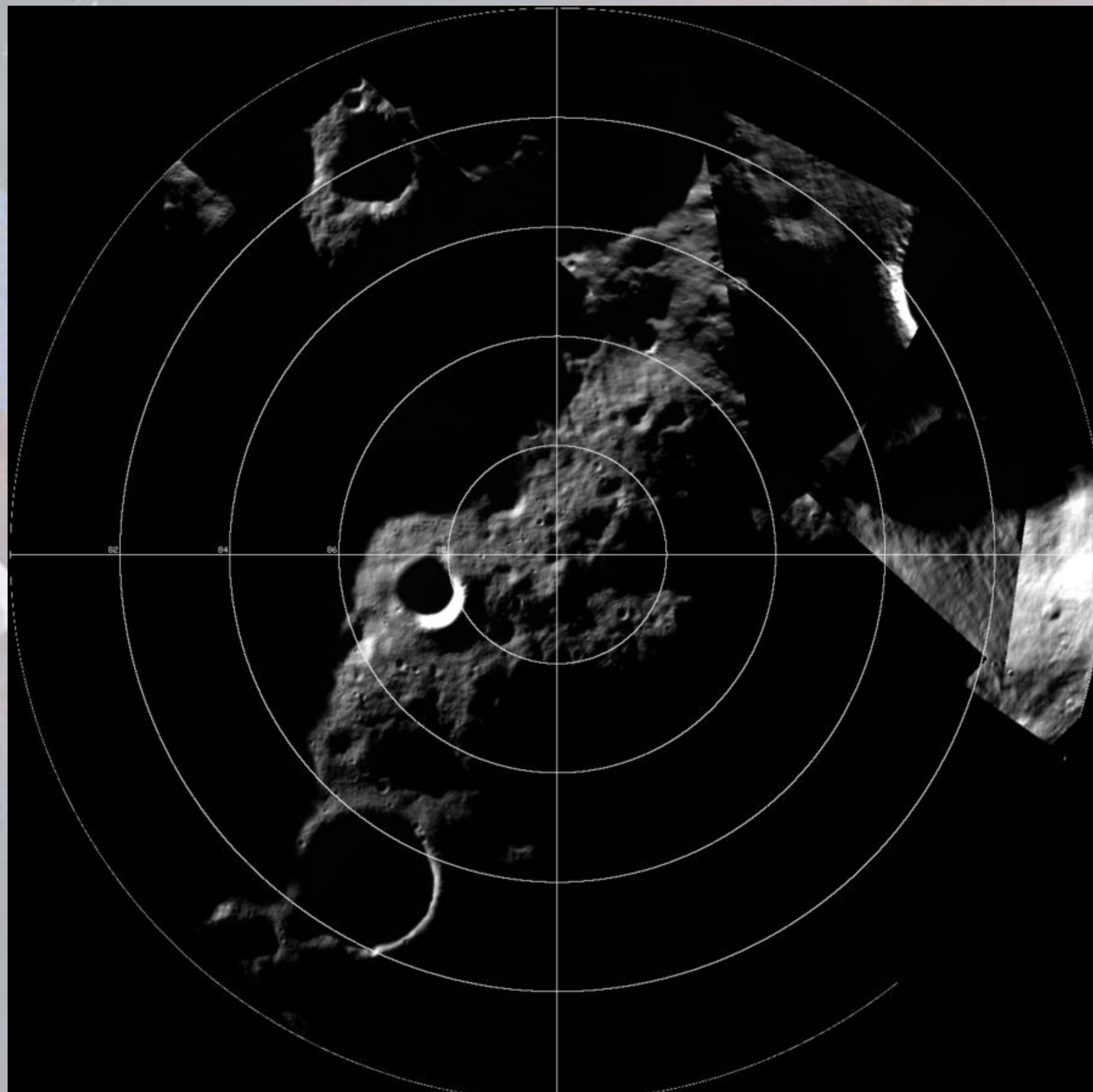
Arizona State University

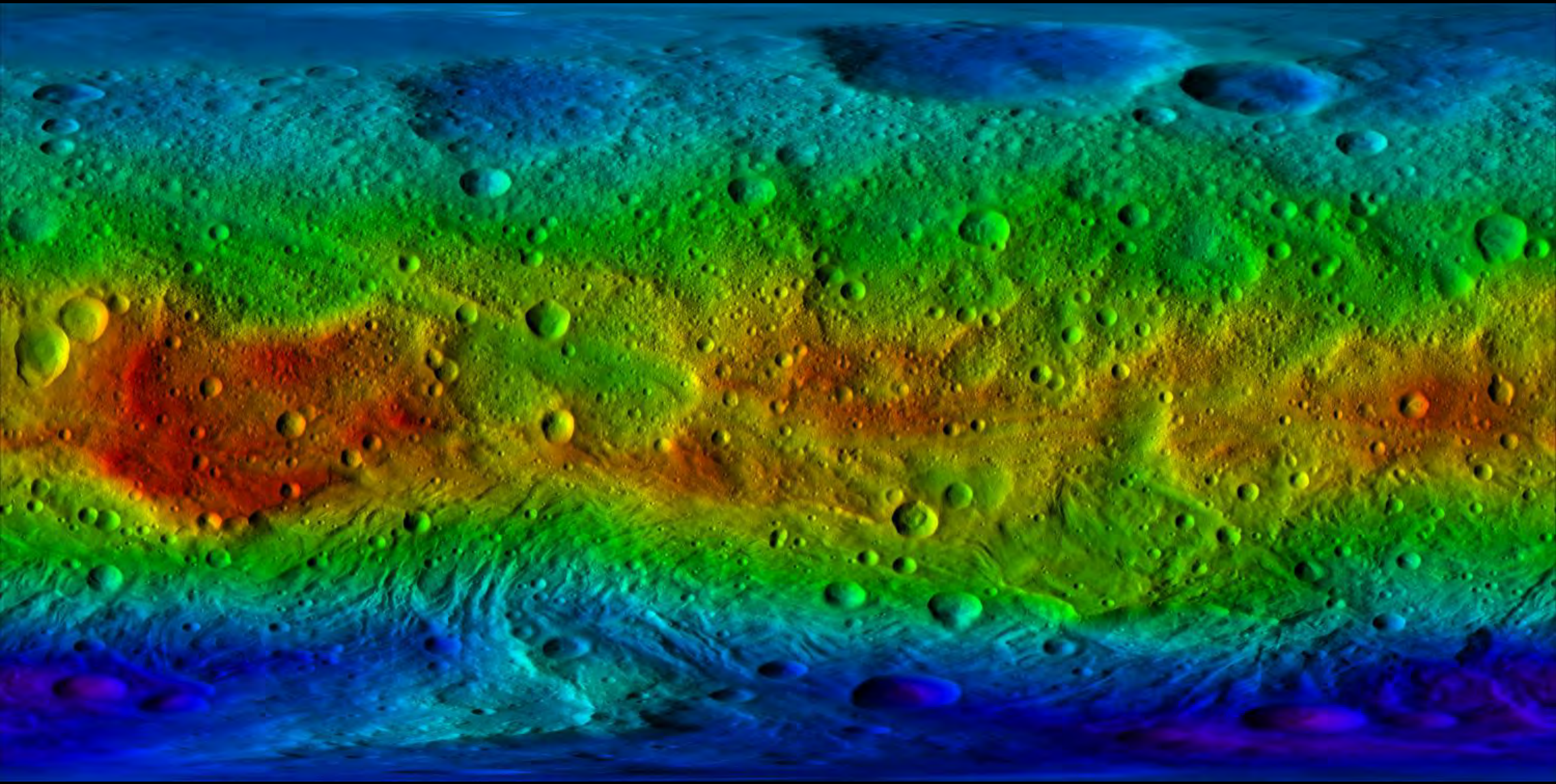
Vesta’s North Pole

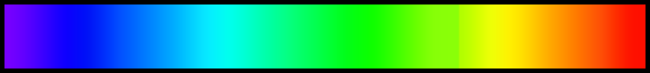
HAMO-2 Orbit



July 24, 2012

GLOBAL GRIDDED MAP (64 pixels/degree)

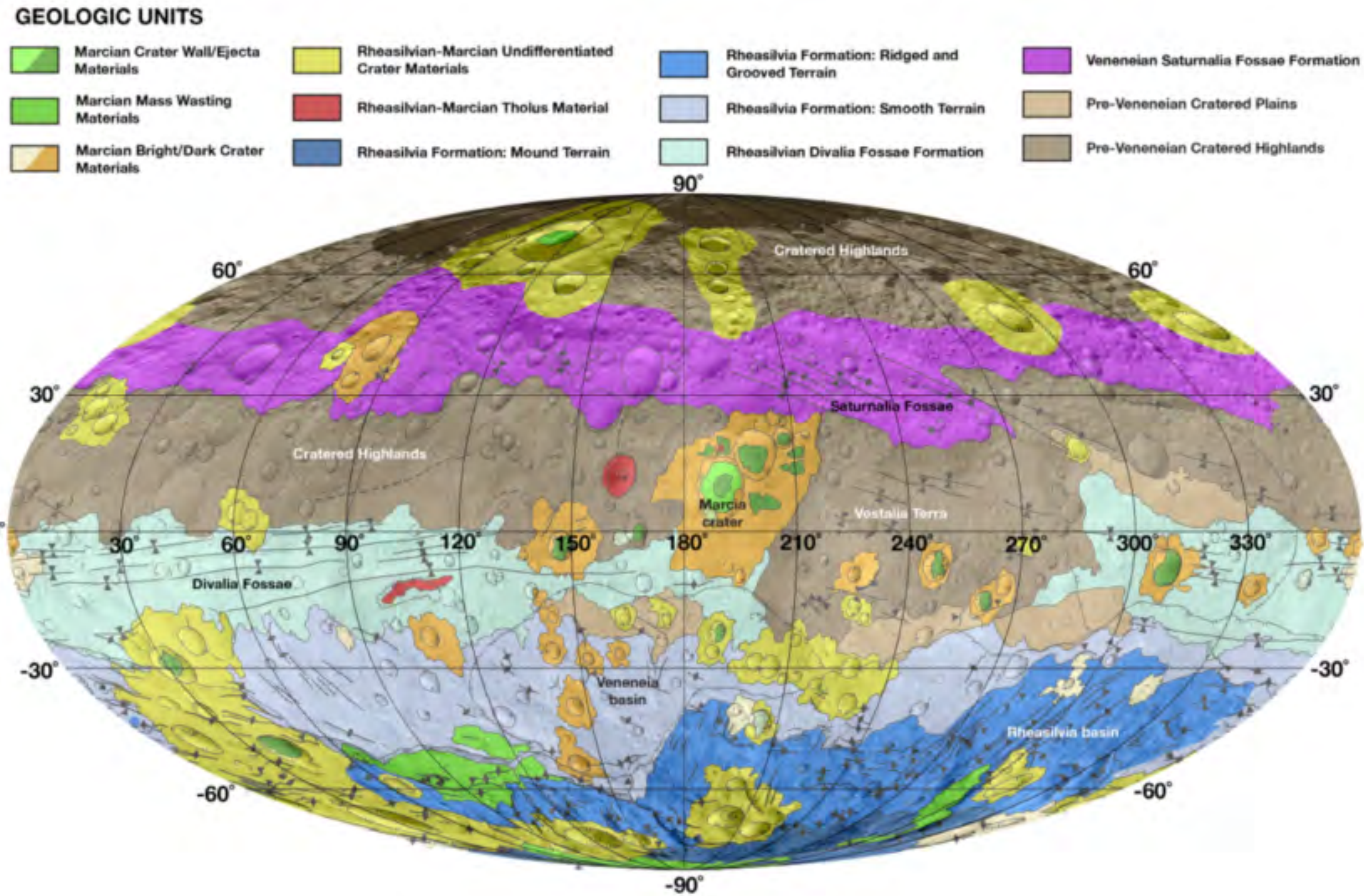




Grid is i=1,23041, j=1,11521
Latitude=(5761-j)/64 degrees
Longitude=(i-11521)/64 degrees
Data is MSB unsigned short from dn=1,65535. dn=0 represents no data.
Radius in km at i,j is
R(i,j)= 250.00000 - 0.3806459373D+02 + (dn(i,j)-1)*0.1234318295D-02

Vesta Global Geologic Map

Modified from Yingst et al., 2014 (in press)

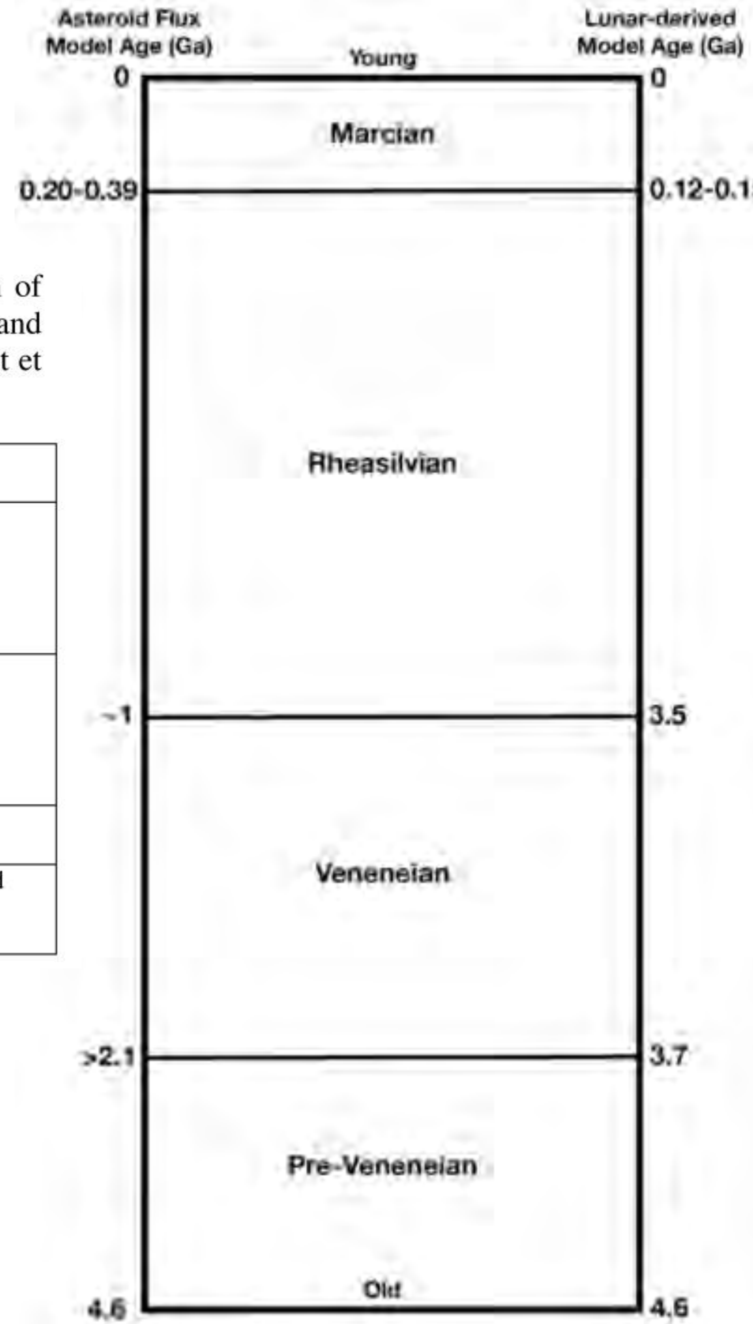


Vesta Chronostratigraphy & Geologic Time Scale

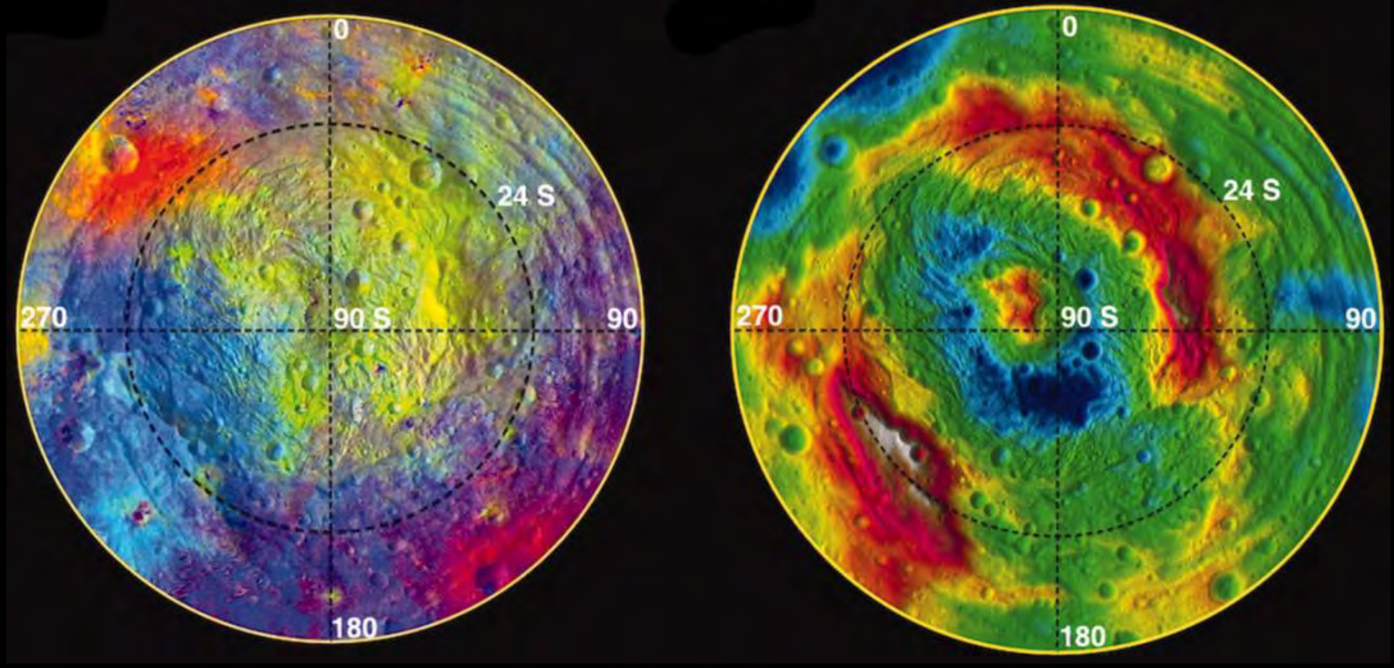
Williams et al. (in press)

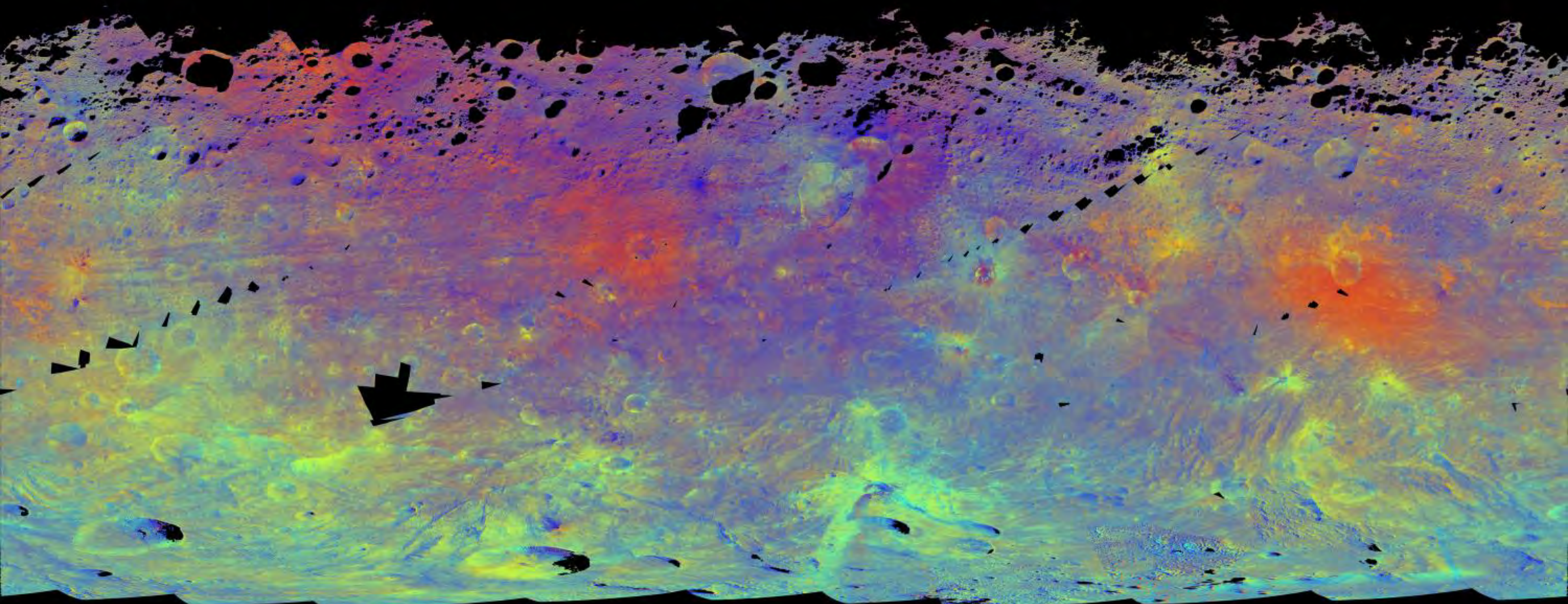
Table 1. Proposed time-stratigraphic scheme for protoplanet Vesta. The correlation of Vesta's rock units, time-rock units, and time units is derived from geologic mapping and other Dawn data analyses (e.g., Jaumann et al., 2012; Buczkowski et al., 2013; Yingst et al., 2014; Williams et al., 2014).

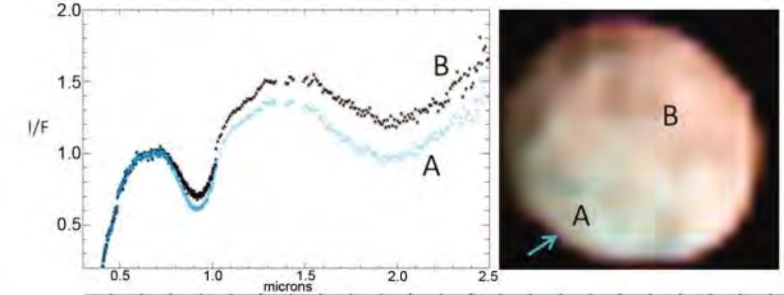
Rock Unit	**Time-Rock Unit**	**Time Unit**
Marcia Formation: Crater Wall and Ejecta Materials, Mass Wasting Materials, Bright and Dark Crater Materials, Undifferentiated Crater Materials, Tholus Material	Marcian System	Marcian Period
Rheasilvia Formation: Smooth, Ridged and Grooved, and Mound Terrains, Divalia Fossae Formation, Undifferentiated Crater Materials, Tholus Material	Rheasilvian System	Rheasilvian Period
Saturnalia Fossae Formation	Veneneian System	Veneneian Period
Cratered highlands & plains, possibly Vestalia Terra	Pre-Veneneian System	Pre-Veneneian Period

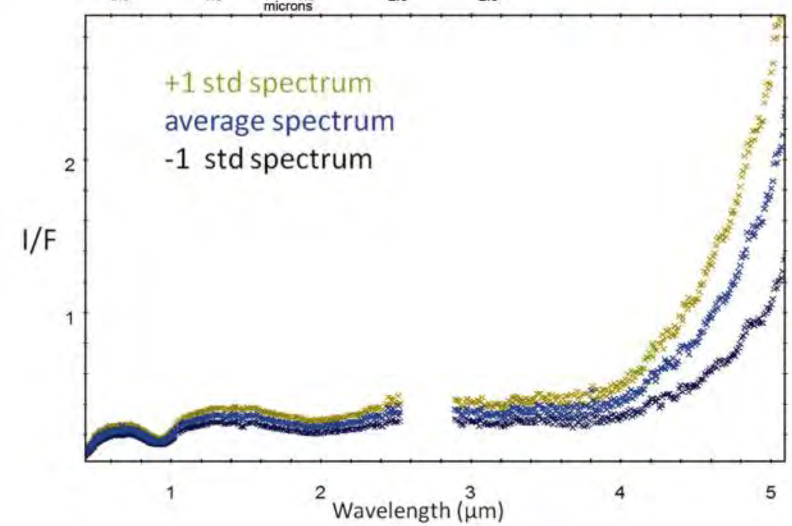


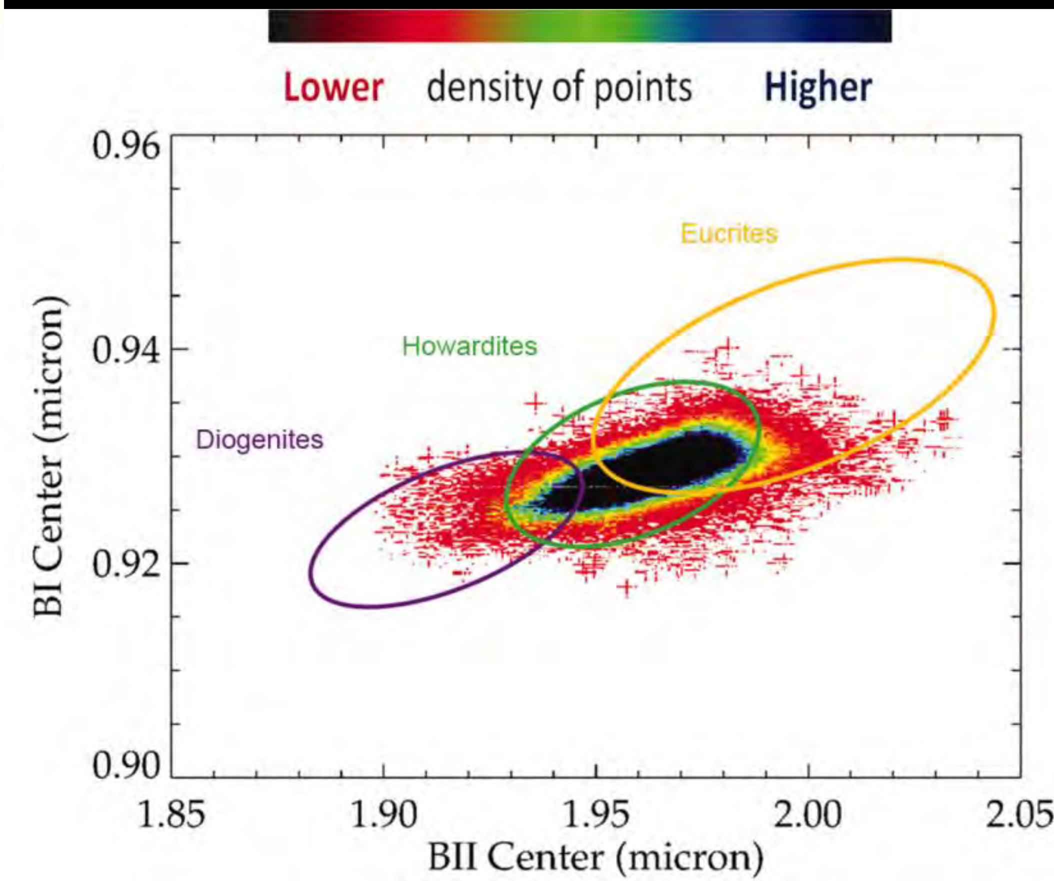
Vesta’s Composition

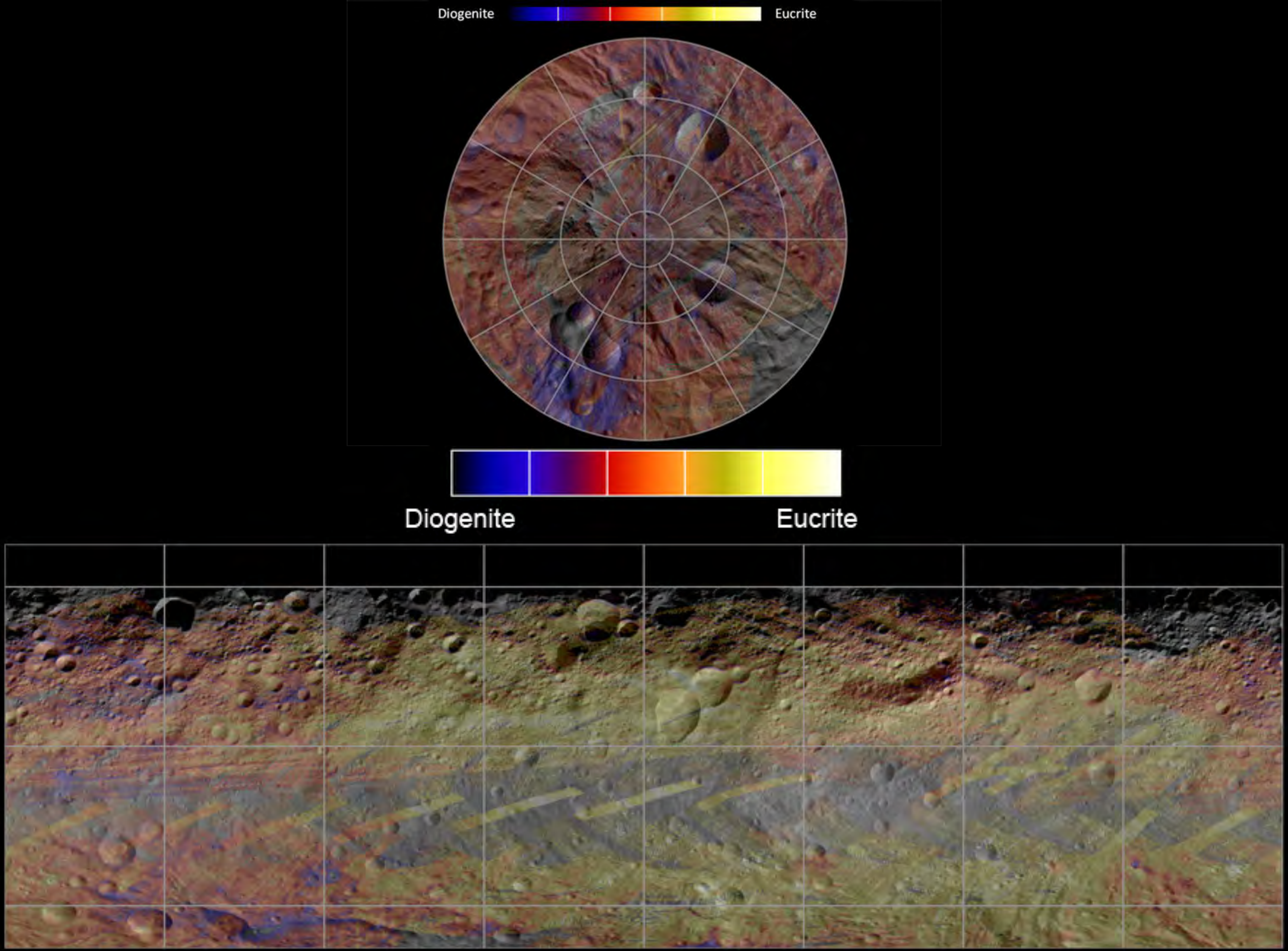

0
24 S
270
90 S
90
180
0
24 S
270
90 S
90
180

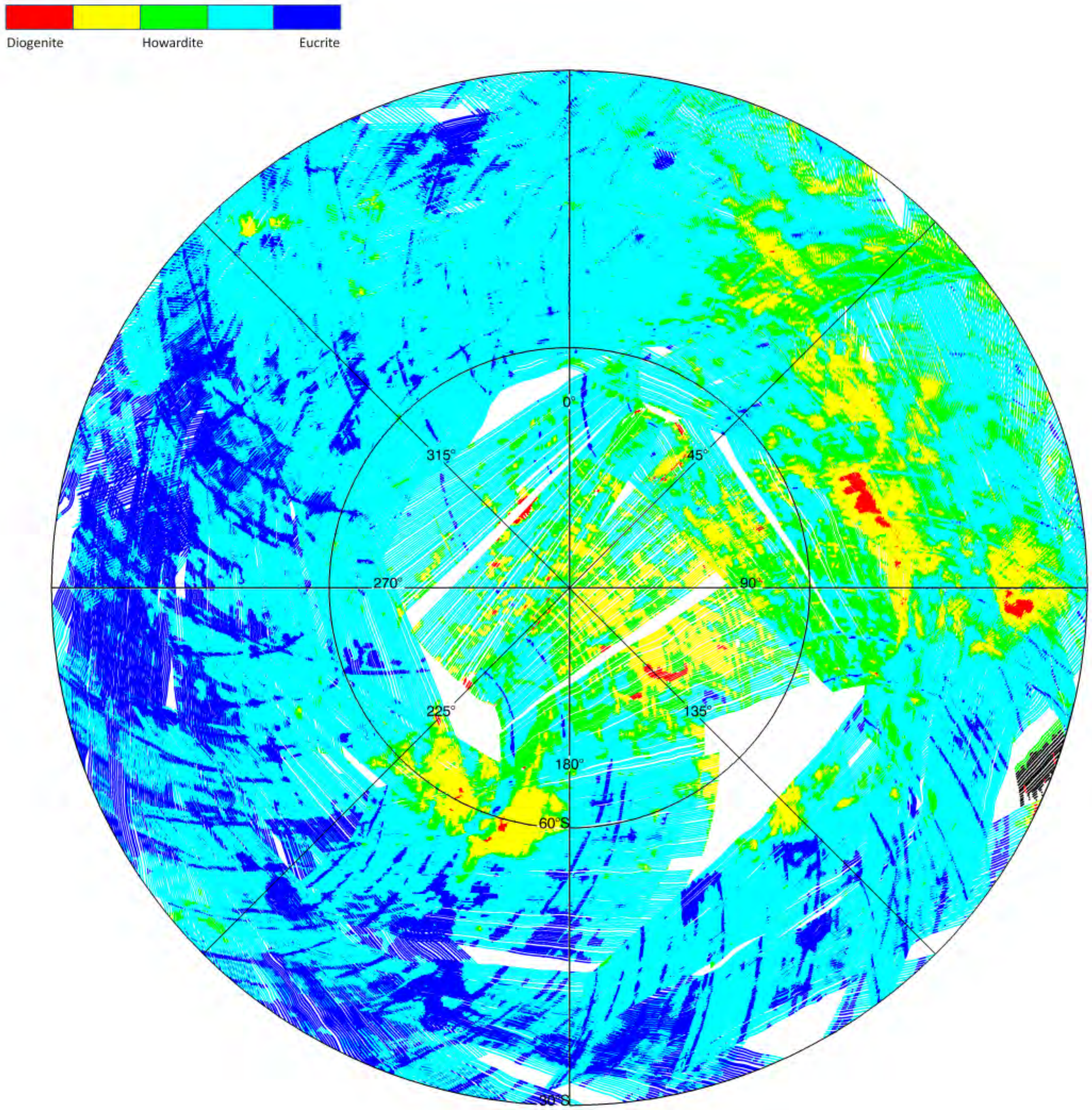



2.0
1.5
1.0
0.5
I/F
0.5
1.0
1.5
2.0
2.5
microns
B
A
B
A


+1 std spectrum
average spectrum
-1 std spectrum
I/F
2
1
1
2
3
4
5
Wavelength (μm)

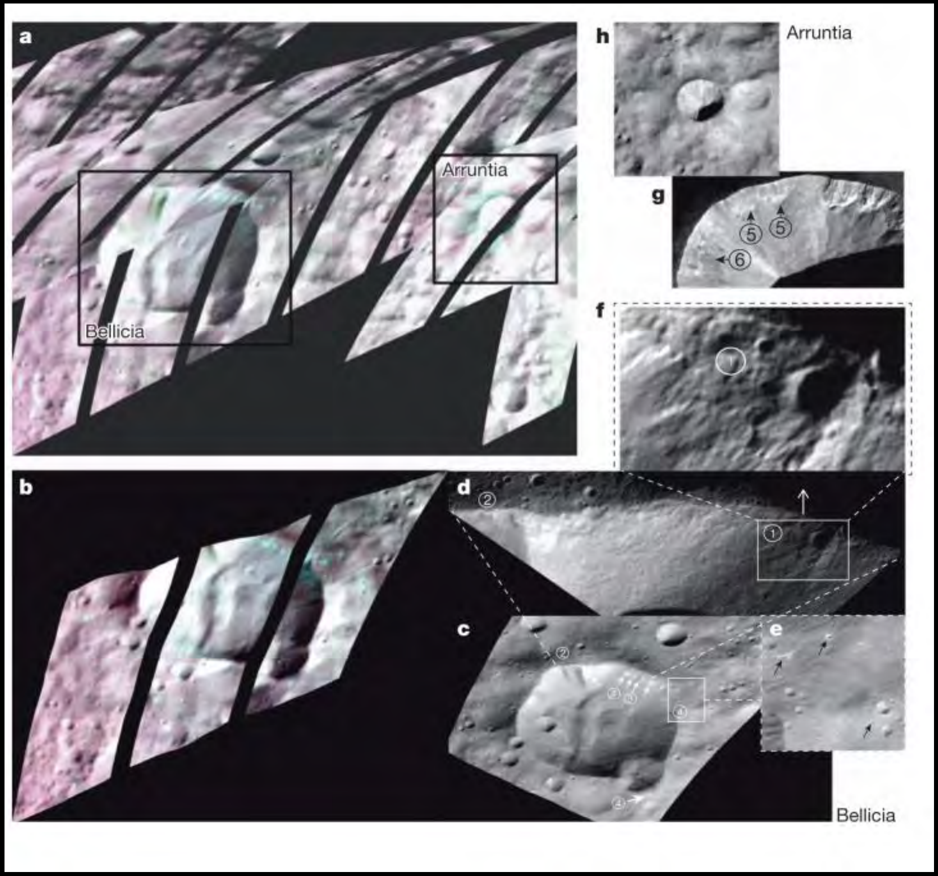

Lower density of points Higher
Eucrites
Howardites
Diogenites
BI Center (micron)
0.96
0.94
0.92
0.90
1.85
1.90
1.95
2.00
2.05
BII Center (micron)


Diogenite
Eucrite
Diogenite
Eucrite

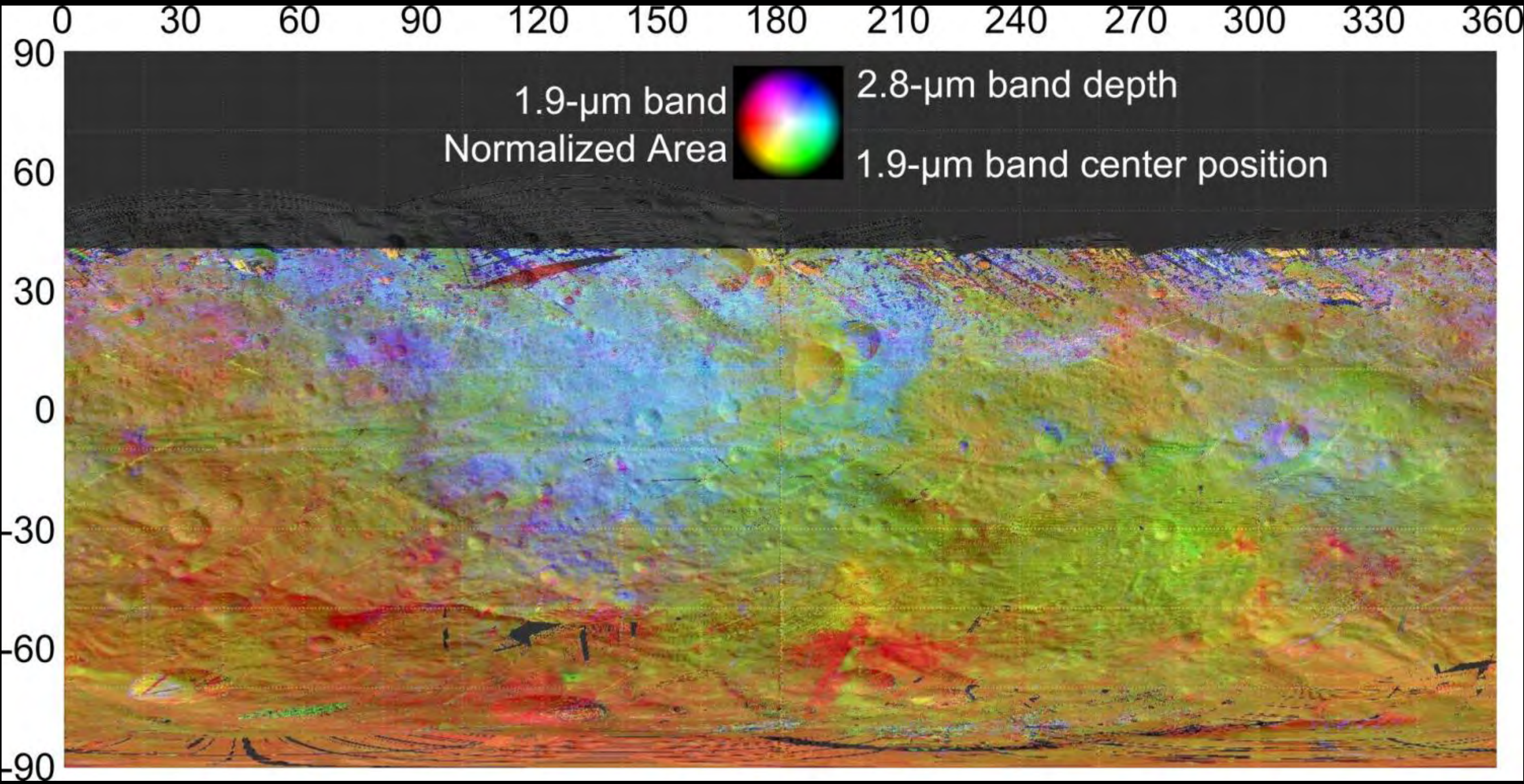


Diogenite
Howardite
Eucrite
0°
45°
90°
135°
180°
225°
270°
315°
60°S
30°S

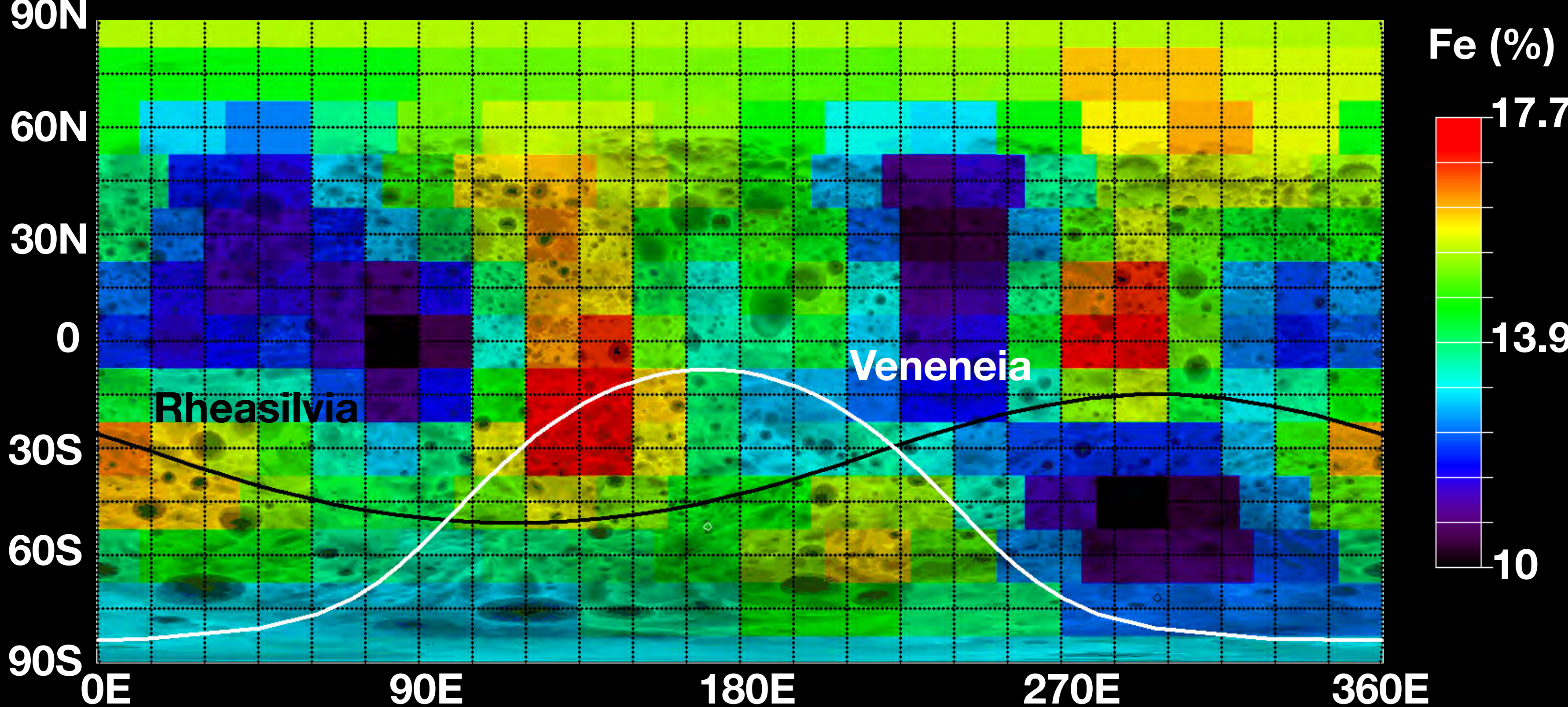
Olivine Detection
Ammannitto et al., 2013 Nature



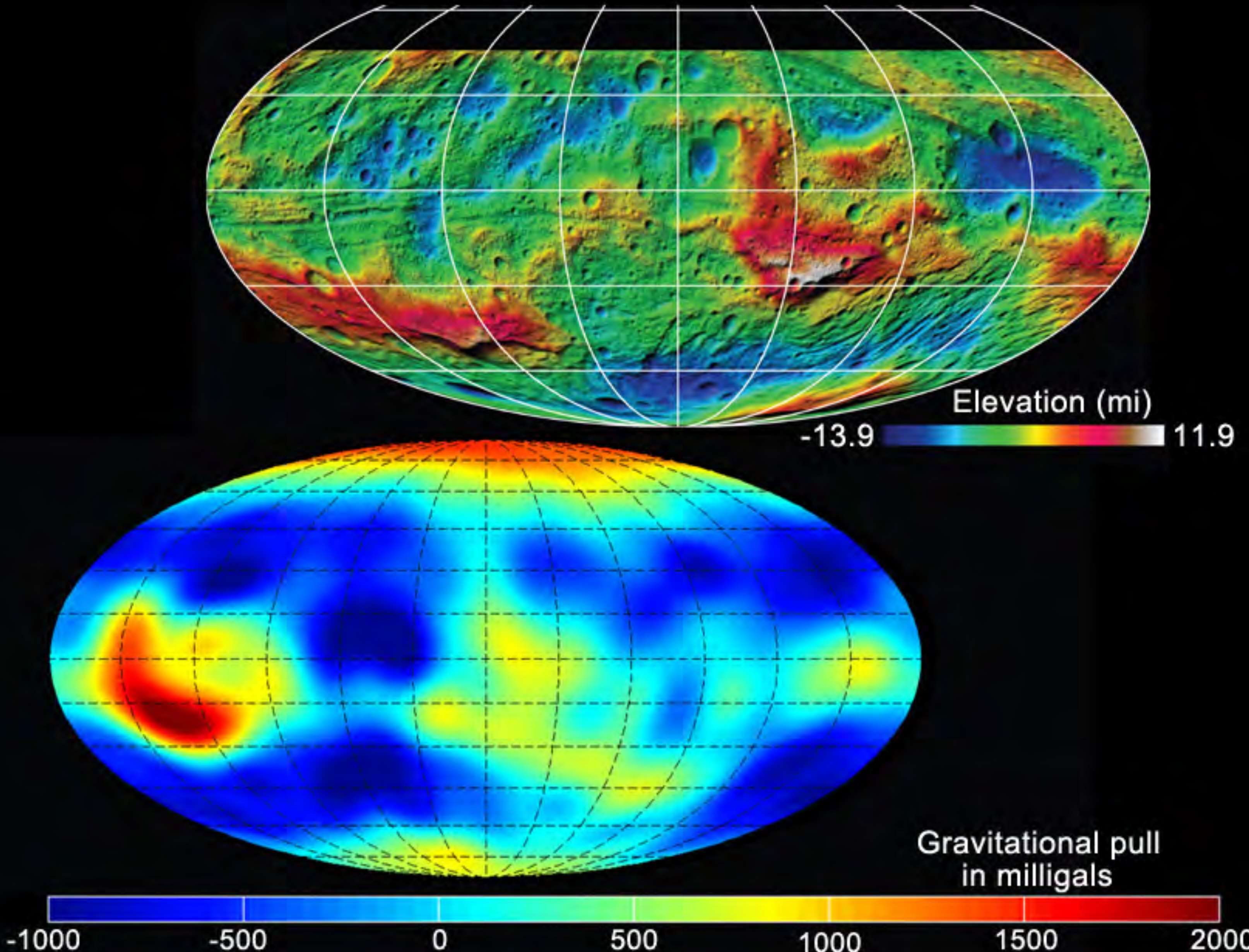
Absorptions by OH and Pyroxene

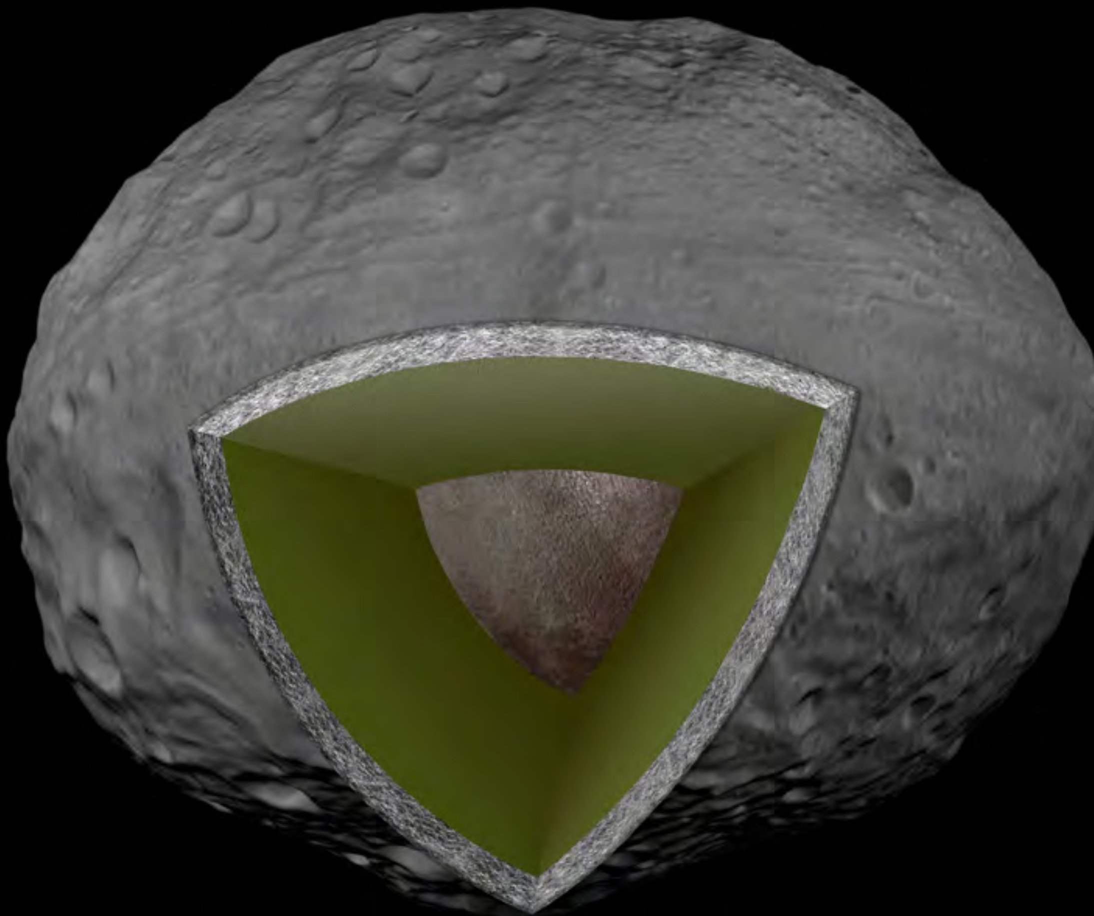


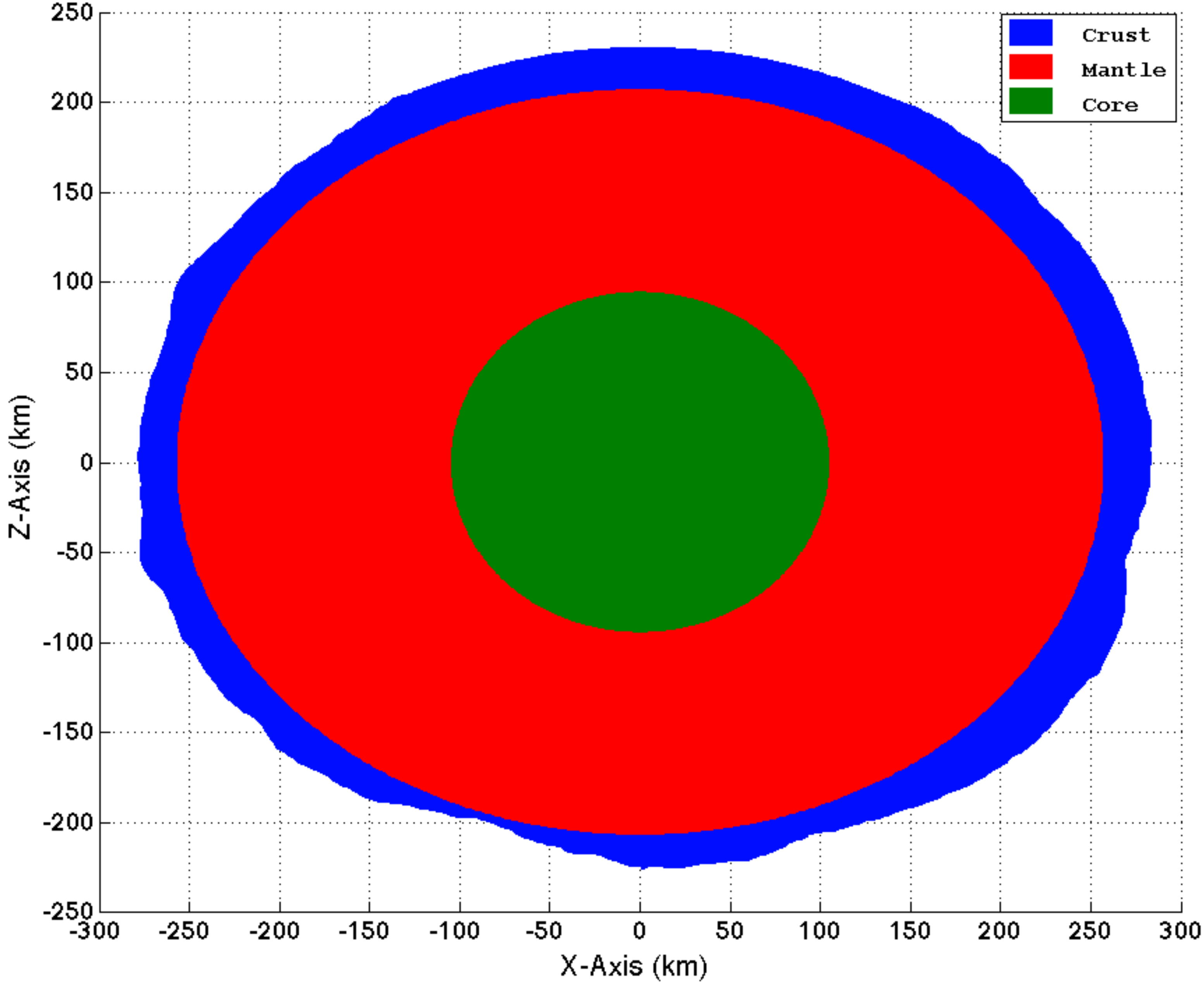
Preliminary GRaND Map of Fe



Vesta’s Gravity and Structure


Elevation (mi)
-13.9
11.9
Gravitational pull
in milligals
-1000
-500
0
500
1000
1500
2000




Crust
Mantle
Core
Z-Axis (km)
X-Axis (km)
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-250
-200
-150
-100
-50
0
50
100
150
200
250
300

Results

- *Dawn* successfully entered Vesta orbit on 16 July 2011
- Survey orbits successfully completed during August 2011
  - No evidence of Vestan moons
  - Surface variation at global scale now known
    - South polar depression with central mound
    - Grooved and disrupted terrain within & surrounding depression
    - Heavily cratered northern plains and equatorial troughs
  - Global topography determined
- HAMO-1 orbit successfully completed by November 1, 2011
- LAMO orbit completed by May 1, 2012
  - 80% of surface imaged at ~20 m/pixel
- *Dawn* Completed HAMO-2 orbit
  - June 15 to July 24, 2012
  - Image north pole & high northern latitudes as they are becoming illuminated
  - Integrate all data sets, complete geologic maps
- Results analyses continuing
- *Dawn* departed for Ceres: Sep 5, 2012

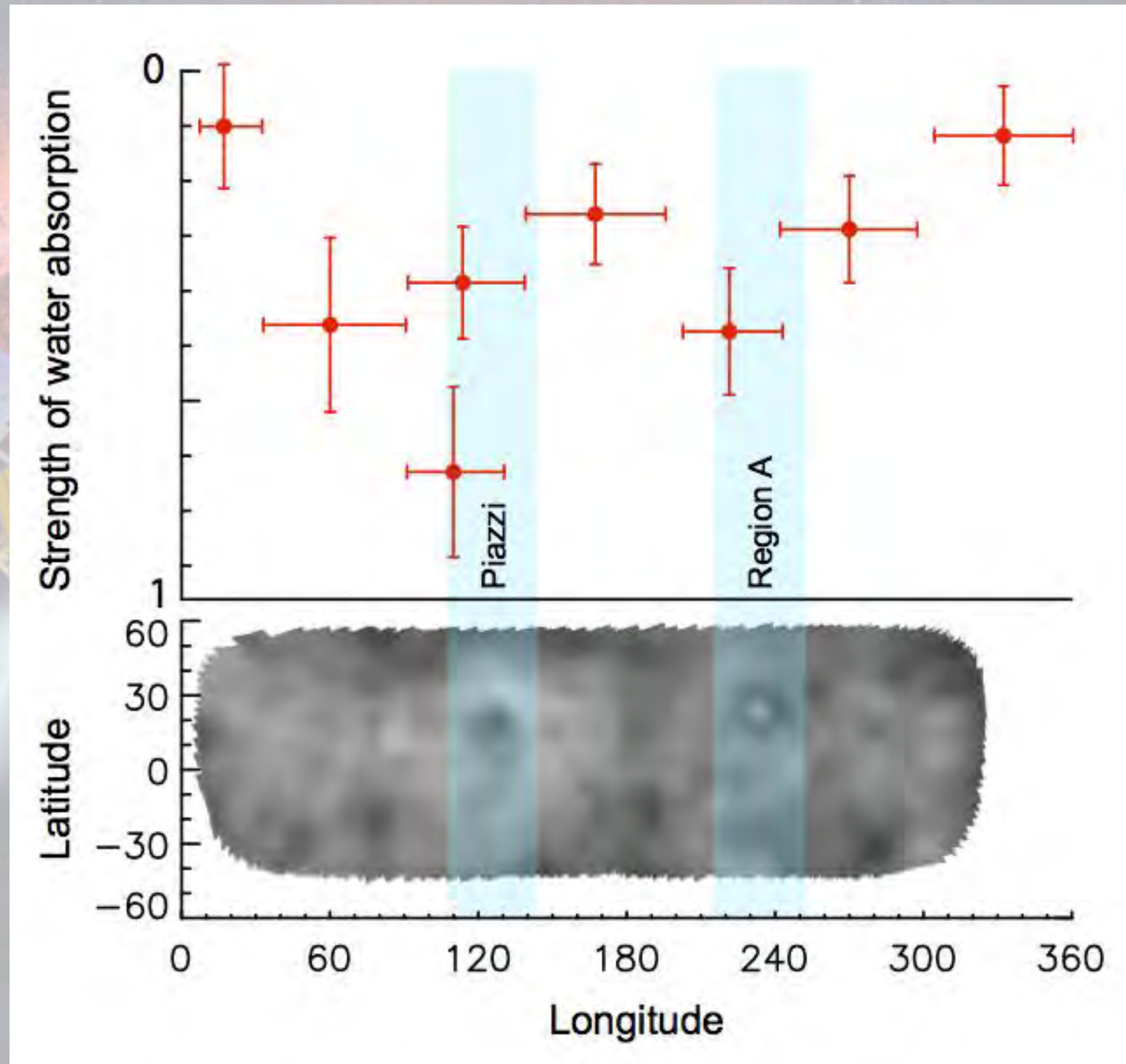
Arrival at Ceres: March 5, 2015 ± 1 wk

On to Ceres!

Water Vapor coming from Ceres!

January 22, 2014

- ESA *Herschel* space telescope detected H2O molecules escaping from two regions of Ceres, 6 kg/s (13 lbs/s)
- Detected when Ceres closer to Sun -> warmer
- Either buried cometary ice or cryovolcanism
- *Dawn* departed for Ceres: 5 Sep 2012
- *Dawn* arrives at Ceres: 23 Mar 2015 (±1 wk)



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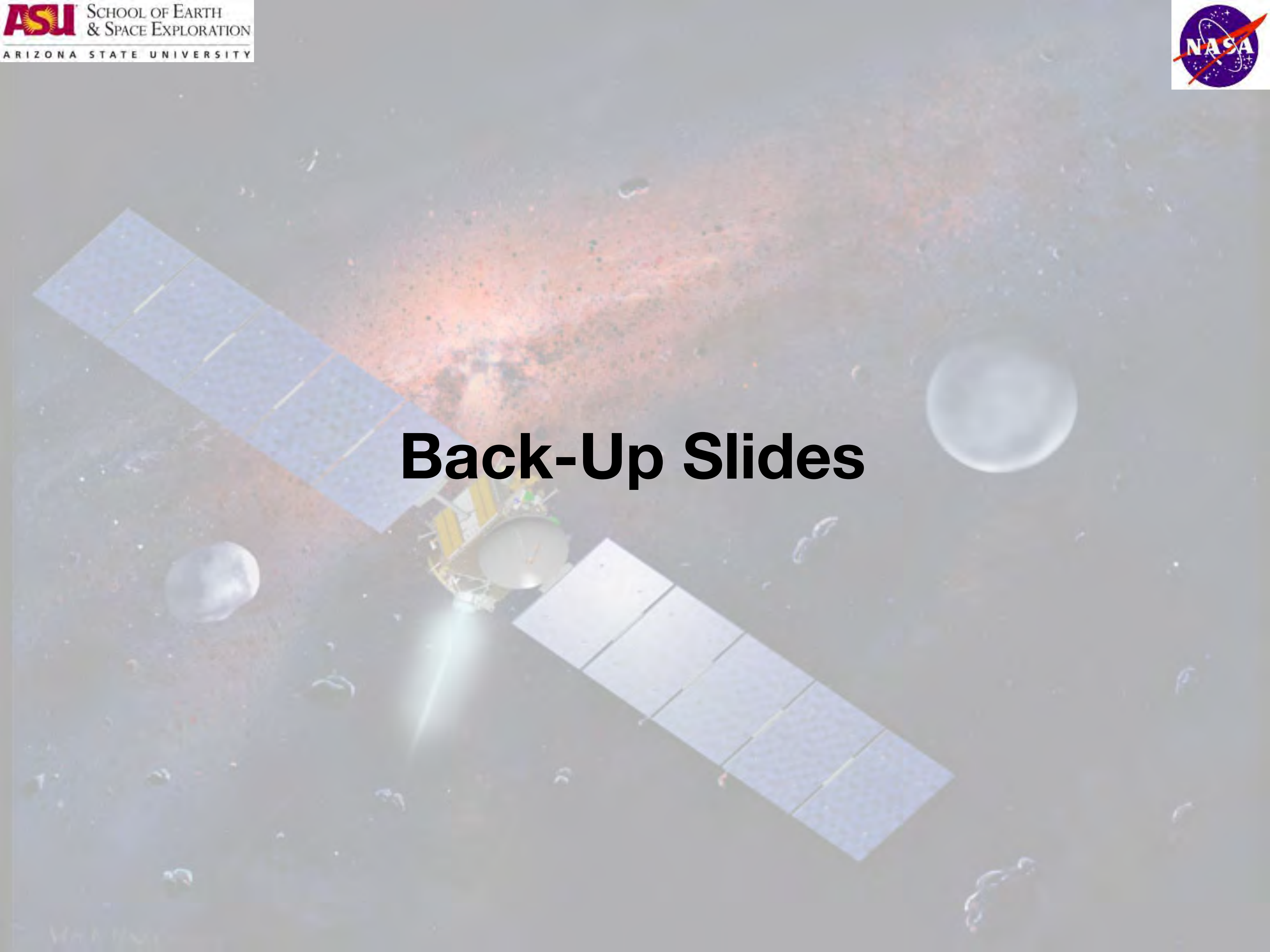
ARIZONA STATE UNIVERSITY



Back-Up Slides

ASU School of Earth & Space Exploration
ARIZONA STATE UNIVERSITY

NASA's Discovery Program

Mission	***Launch Date***	***Mission Type***	***Comment***
NEAR	17Feb'96	Asteroid Orbiter	Orbited & landed on Eros
Mars Pathfinder	04Dec'96	Lander/Rover	First airbag landing; test rover for MER
Lunar Prospector	06Jan'98	Orbiter	Seek H_2O at lunar poles
Stardust	07Feb'99	IDP/comet Flyby & sample return	Returned samples from Comet Wild 2, 15Jan'06; Comet Tempel 1 flyby on 14Feb'11 (Stardust-NeXT)
Genesis	08Aug'01	Solar Wind Sample Return	Returned 08Sep'04
CONTOUR	03Jul'02	Multiple Comet Flybys	SRM Failed
MESSENGER	**03Aug'04**	**Orbiter**	**First Mercury Orbiter**
Deep Impact	12Jan'05	Comet Orbiter/Impactor Flyby (EPOXI)	Imp Tempel 1 04Jul'05; Hartley 2 flyby 04Nov'10
Dawn	**27Sep'07**	**Asteroids Orbiter**	**Vesta 16Jul'11**
Kepler	**06Mar'09**	**Orbiting telescope**	**Earth-sized planets**
GRAIL	**08Sep'11**	**Paired Orbiters**	**Lunar gravity field**
InSight	**Mar '16**	**Stationary Lander**	**Mars geophysics**

Bold = active or completed mission; Red = Failed Mission